

# VIRGINIA JOURNAL OF SCIENCE

OFFICIAL PUBLICATION OF THE VIRGINIA ACADEMY OF SCIENCE

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Vol. 63

No. 3 & 4

Fall/Winter

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# **Late Holocene Sedimentation and Paleoenvironmental History for the Tidal Marshes of the Potomac and Rappahannock Rivers, Tributaries to Chesapeake Bay**

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## **ABSTRACT**

Instrumental tide gauge records indicate that the modern rates of sea-level rise in the Chesapeake Bay more than double the global average of 1.2-1.5 mm yr<sup>-1</sup>. The primary objective for this study is to establish a relative depositional history for the tidal marshes of the Potomac and Rappahannock Rivers that will help us improve our understanding of processes that influence sedimentation in the proximal tributaries of Chesapeake Bay. Marsh cores were collected from Blandfield Point VA, Tappahannock VA, and Potomac Creek VA. The sedimentary facies include: 1) a lower unit of organic-poor, grey clay with fine sand and silt layers and estuarine foraminifera; and 2) an upper unit of organic-rich clay and peat with abundant brackish to freshwater marsh foraminifera and thecamoebians. AMS 14C dating of bulk marsh sediments yield sedimentation rates at Potomac Creek ranging from 3.04-4.20 mm yr<sup>-1</sup> for the past 2500 years. Rates of sedimentation calculated for Blandfield Point indicate 1.37-2.19 mm yr<sup>-1</sup> in the basal clays and peat for the past ~3000 years. Foraminiferal census counts indicate a freshening upward trend with a transition from an estuarine *Ammobaculites crassus* assemblage to a marsh *Ammoastuta salsa* assemblage with abundant freshwater Thecamoebians. The late Holocene history of sedimentation for the marshes indicates that differential compaction, recent land use practices, and climate change have contributed to the resultant freshening-upward environmental trend and variability in sediment accumulation rates between coring sites.

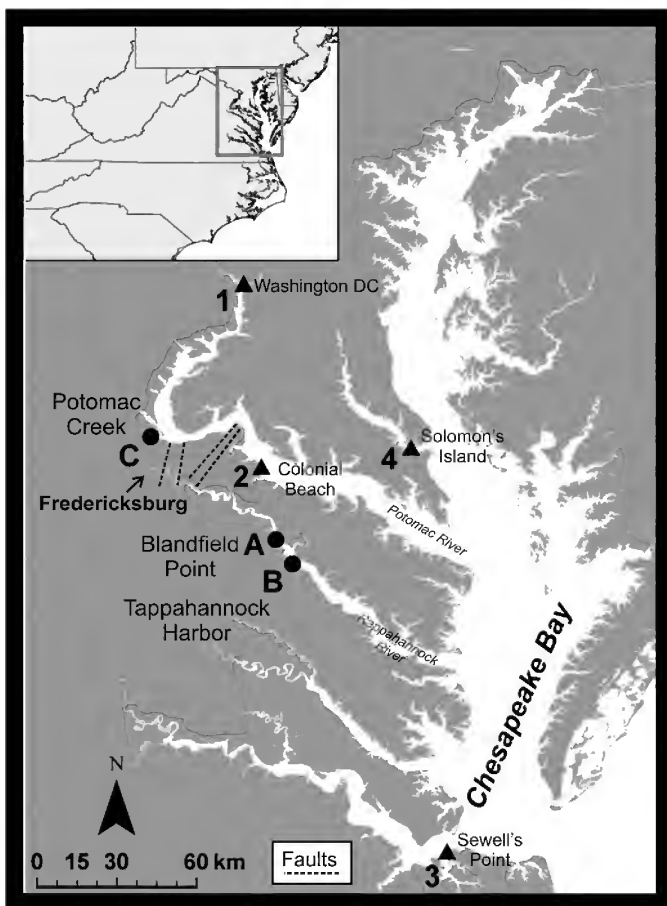


FIGURE 1. Location map for the tidal reaches of the Potomac and Rappahannock Rivers. Table 1 lists the coordinates and detailed coring information for Sites A-C. Table 2 lists coordinates and details for the tide gauge stations (Sites 1-4). Inset shows our location along the eastern Atlantic coast of the USA.

## INTRODUCTION

The Chesapeake Bay watershed comprises numerous tributaries draining from the eastern Appalachian Mountains. The central axis to the Chesapeake has been evaluated in the context of decadal, centennial, and millennial climate changes (Cronin and others 2005, 2010). In the historic Northern Neck region of Virginia, the tidal reaches of the Rappahannock and Potomac Rivers (Fig. 1) have received little detailed study with respect to the nature of the sedimentary record spanning the past several thousand years. Recent estimates for eustatic sea level are estimated to be as high as  $1.5\text{--}1.88\text{ mm yr}^{-1}$  (Church and White 2006, Nerem and others 2006) whereas the instrumental tidal

TABLE 1. List of sampling localities from the Potomac and Rappahannock tidewater region of Virginia and Maryland.

Site	Location	Longitude	Latitude	Geographic Info
Site A	Blandfield Point VA	76°54'40.436"W	38°0'6.911"N	Blandfield Marsh on Rappahannock River (proximal estuarine zone 0-5 ppt)
Site B	Tappahannock Harbor VA	76°51'15.368"W	37°55'16.723"N	Coleman's Island, Hoskin's Creek tributary to Rappahannock River (distal tributary to central estuarine zone)
Site C	Potomac Creek VA	77°20'7.619"W	38°21'6.972"N	Potomac Creek tributary to Potomac River (central estuarine zone 5-15 ppt)

records from the Chesapeake Bay indicate rates as high as  $\sim 3\text{--}4\text{ mm yr}^{-1}$  (Boon 2012). The disparity between global and regional base level change in the Chesapeake Bay is not well understood and likely reflects the combined effects of allogenic, autogenic, and anthropogenic processes in the region (Cronin 2012). The primary objective for this paper is to establish a late Holocene sedimentation and paleoenvironmental history for the tidal reaches of the Potomac and Rappahannock Rivers in the Northern Neck region of Virginia, USA. Our primary analytical tools include physical stratigraphy (loss on ignition, grain size, and magnetic susceptibility), foraminiferal paleoecology, and AMS  $^{14}\text{C}$  geochronology applied to cores collected from the central estuarine region of the tidal Potomac and Rappahannock Rivers.

## BACKGROUND

The Chesapeake Bay is the largest estuary in the United States, with shores bordering the states of Virginia, Maryland, and the District of Columbia. The watershed area of this coastal plain estuary is  $167,000\text{ km}^2$  that includes the following major tributaries: Susquehanna, Potomac, Rappahannock, York, and James Rivers (Boesh and others 2001). The Chesapeake Bay is the product of Holocene sea-level rise formed by fluvial incision coupled with the inundation of river valleys following the terminus of the last glacial maximum (Schubel and Pritchard 1986). The Chesapeake Bay is located in an apparently inactive tectonic region on the North American passive margin. However, many Cretaceous age faults have been identified in close proximity to our localities in the Fredericksburg, VA (Table 1) which marks the transition from the Piedmont region (west) to the coastal plain (east) in Virginia (Fig. 1) (Berquist and Bailey 1999). Lower Tertiary sedimentary deposits in the region include fine-to coarse glauconitic quartz sand and clay-silt of the Lower Tertiary Pamunkey Group (Brightseat, Aquia, Marlboro, Nanjemoy, and Piney Point formations) (Mixon and others 1989).

TABLE 2. Tidal gauge data for the Chesapeake Bay (NOAA, 2009).

Locality	Instrumental Records	SL Rate mm yr <sup>-1</sup>	YBP	Tidal Station & Data Set Info NOAA Monthly Mean
1	Washington DC	3.16±0.35	87	8594900 (1924-2006)
2	Colonial Beach VA	4.78±1.21	39	8635150 (1972-2003)
3	Sewells Point VA	4.44±0.27	84	8638610 (1927-2006)
4	Solomons Island MD	3.41±0.29	74	8577330 (1937-2006)
*	Global average	1.5±0.5	0	

During the past several decades, the National Oceanic and Atmospheric Administration (NOAA, 2009) has maintained tidal gauging stations at Colonial Beach and Washington DC (Table 1). The sea level rates calculated from the instrumental records on the Potomac River range from 3.16-4.78 mm yr<sup>-1</sup> from Washington DC and Colonial Beach respectively (Table 2), which are significantly higher than eustatic values of 1.0-1.5 mm yr<sup>-1</sup> (Table 2) (NOAA 2009; Boon 2012). The instrumental records from the lower Rappahannock at Sewell’s point record a relative sea-level rise of 4.44 mm yr<sup>-1</sup> spanning the past 84 years.

Cronin and others (2000, 2005, and 2010) and Cronin and Vann (2003) reported microfossils from cores (~2-6 m in thickness) located at the mouths of the major tributaries in the central regions of the bay (e.g., Patuxent, Choptank, and the Potomac Rivers). Willard and others (2003) and Cronin and others (2003) reported a high-resolution historical microfossil record that apparently discriminates important anthropogenic events such as the Medieval Warm Period and deforestation of the bay region with the arrival of European settlers.

METHODS

Marsh cores were collected from the Rappahannock and Potomac Rivers that includes Blandfield Point (Site A), Tappahannock Harbor (Site B), and Potomac Creek (Site C) (Table 1) (Fig. 1). A square-rod piston coring device was used to collect continuous 1-meter long core drives down a single coring hole (Wright 1967). Individual core sections were split along a longitudinal axis to produce two equal halves. Potomac Creek cores were evaluated for microfossils at 10 cm intervals. Approximately eighty 1cm<sup>3</sup> sediment samples were soaked in a beaker of warm water and mild detergent to disperse the clays (Scott and Leckie 1990). Samples were rinsed over a 63 µm sieved and picked wet using conventional microfossil methods (Scott and Medioli 1980). Each sample was then examined for foraminifera and relative abundances were calculated for species and select genera to simplify the trends. Exceptionally preserved specimens were examined on the scanning electron microscope (SEM) for identification and illustration purposes.

The total organic matter (TOM) was determined by using loss on ignition (LOI) (Dean 1974). Grain size analyses were conducted using methods modified from McManus (1988). Volume magnetic susceptibility was conducted on sediments using a Bartington MS2E surface scanner following the method of split-core logging of Last and Smol (2001). Select bulk sediment samples were pretreated for radiocarbon dating at the University of Pittsburgh following the methods outlined by Abbott and Stafford (1996). AMS  $^{14}\text{C}$  analyses were performed at the University of Arizona's Accelerator Mass Spectrometry Laboratory and the dates calibrated using Calib 6.1.0 (Reimer and others 2009).

## RESULTS

### Sedimentary Facies

**Grey Clay Facies:** The basal sediments at all coring sites comprise clay and sparse interbeds of silt and sand (Fig. 2). The grey clay facies ranges in thickness from ~7.5-4.25 m at Potomac Creek to ~5.5-2.5 at Tappahannock Harbor (Fig. 2). TOM values in the organic-rich clay range from ~8-28%. Magnetic susceptibility values are relatively low with positive excursion peaks in the silt-rich layers. Grain size analyses at Tappahannock Harbor indicate a coarsening-up trend from mud-to-silt and fine sand (Fig. 2). Foraminifera in the organic-rich grey clay are dominated by *Trochammina inflata*, and *Ammobaculites* spp. in association with sparse *Ammonia* and *Miliammina fusca*. (Fig. 3).

**Peat & Clay Facies:** All cores contain an upper unit of alternating peat and grey clay with TOM values that range from ~20% to 85% (Fig. 2). Magnetic susceptibility values are relatively low with little variability. Microfossil populations in this facies are dominated by *Ammonia* and *Miliammina fusca*. *Trochammina inflata* and *Jadammina macrescens* are also common while *Haplophragmoides* is the least abundant (Fig. 3). Sedimentary cores from Blandfield Marsh and Potomac Creek (Fig. 2) are capped with an uppermost rooted zone of the grass *Phragmites* and the freshwater thecamoebian *Arcellacea* sp. (Figs. 2, 3).

### Core Chronology & Sedimentation Rates

Accelerator Mass Spectrometry (AMS)  $^{14}\text{C}$  dates obtained from Blandfield Point, Tappahannock Harbor, and Potomac Creek are listed in Table 3. Blandfield Point (Site A) yielded a basal age of  $3100 \pm 50$  ybp. Tappahannock Harbor and Potomac Creek yielded basal ages of  $2658 \pm 43$  and  $2725 \pm 25$   $2430 \pm 25$  ybp respectively. The uppermost samples at Potomac Creek (Site C) and Tappahannock Harbor (Site B) were determined to be post-bomb and are therefore excluded from our sediment accumulation rate analysis. Rates of sedimentation were calculated using the cal BP  $^{14}\text{C}$  dates and the respective core depths (Fig. 4). Potomac Creek yielded the highest rates of 3.04-4.20  $\text{mm yr}^{-1}$  for the past  $2430 \pm 25$  years. Both Blandfield Point and Tappahannock Harbor yield sedimentation rates that were relatively consistent during the past several thousand years (1.48-1.65  $\text{mm yr}^{-1}$ ) approaching those for estimates for late Holocene sea-level rise (Table 3).  $^{137}\text{Cs}$  dates obtained in contiguous estuarine cores at Potomac Creek (Site C) and Blandfield Point (Site A) yielded sedimentation rates of 5.4  $\text{mm yr}^{-1}$  and 4.5  $\text{mm yr}^{-1}$  respectively (Tibert and others 2013).

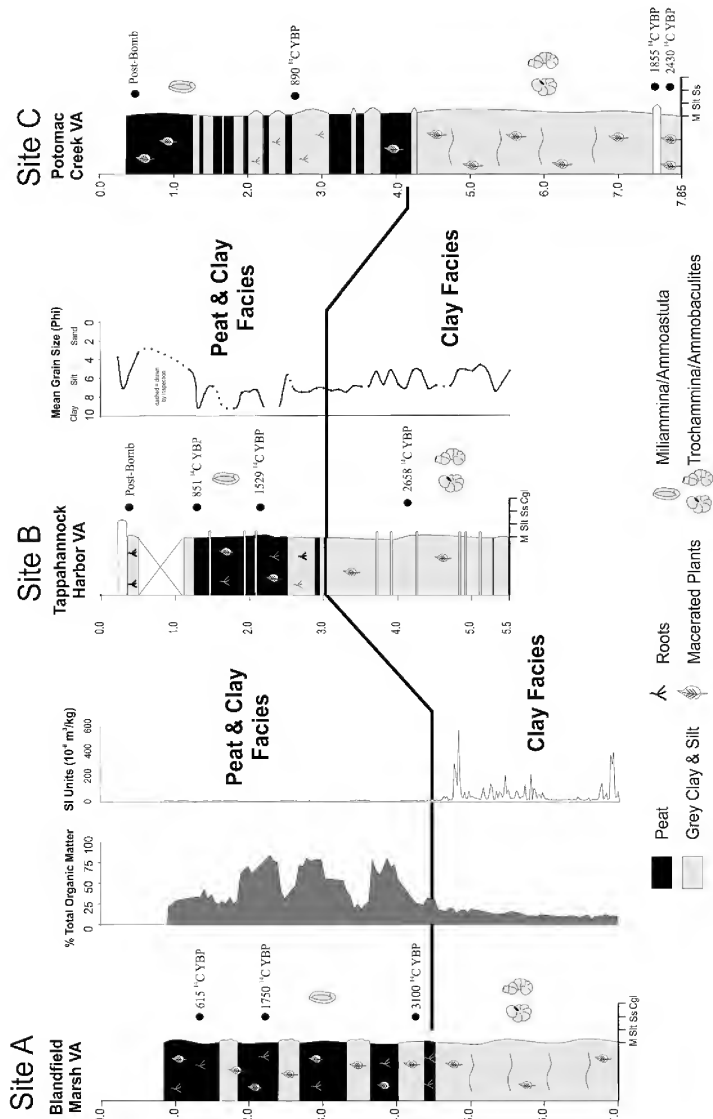


FIGURE 2. Physical stratigraphy of the sedimentary cores collected from the Rappahannock River (Site A Blandfield Point; Site B Tappahannock Harbor) and the Potomac River (Site C Potomac Creek VA). Locality information is listed in Table 1. Details on the AMS Carbon 14 radiometric dates are listed in Table 3.



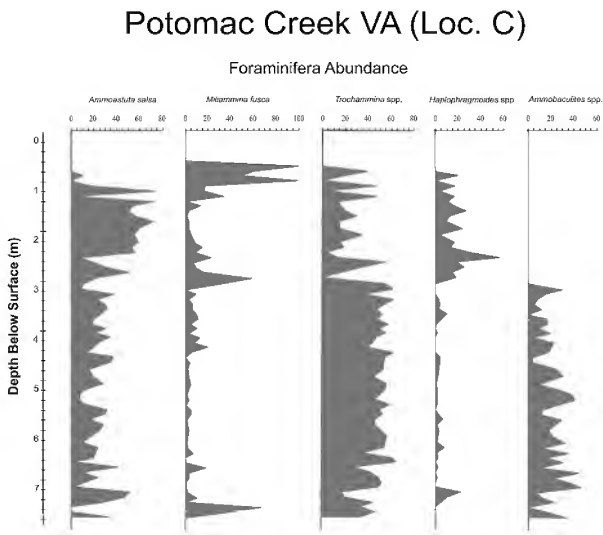


FIGURE 3. Relative abundance plots for the foraminifera recovered from Site C at Potomac Creek, VA.

TABLE 3. AMS <sup>14</sup>C dates and calculated rates of sedimentation for the Rappahannock and Potomac River marshes. Calibrations were performed using Calib 6.1.0 (Reimer and others, 2009).

Location	Sample #	Strat. Hgt (cm)	AMS <sup>14</sup> C	1σ cal. age ranges	unc. <sup>14</sup> C Sed. Rate mm yr <sup>-1</sup>	cal. <sup>14</sup> C Sed. Rate mm yr <sup>-1</sup>
Blandfield Point VA	RA-07-C2-132	132	615±20	cal BP 557-648	2.15	2.19
	RA-07-C3-231	231	1750±20	cal BP 1623-1703	1.32	1.39
	RA-07-C5-456	456	3100±50	cal BP 3263-3377	1.47	1.37
Tappahannock VA	RA-05-C1-0.37	37	post-bomb	NA	NA	NA
	RA-05-C@-1.31	131	851±58	cal BP 692-894	1.54	1.65
	RA-05-C3-2.29	229	1529±41	cal BP 1359-1511	1.50	1.60
	RA-05-C5-4.12	412	2658±43	cal BP 2743-2838	1.55	1.48
Potomac Creek VA	PT-08-PC1	50	post-bomb	NA	NA	NA
	PT-08-PC1	263	890±20	cal BP 744-897	2.96	3.21
	PT-08-PC1	747	1855±20	cal BP 1737-1824	4.03	4.20
	PT-08-PC1	762	2430±25	cal BP 2361-2648	3.14	3.04

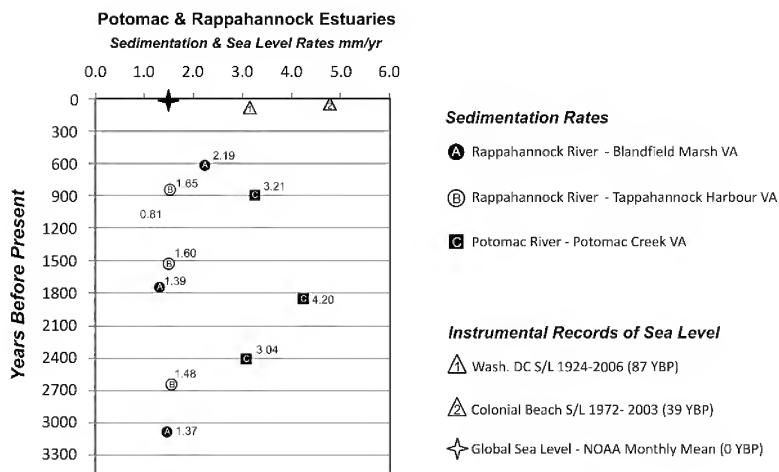


FIGURE 4. Sedimentation rates for the Potomac and Rappahannock marshes in Virginia and Maryland. Tables 1 and 2 list the coring site details and the tide gage station information (NOAA). Sites A-B from the Rappahannock River sedimentation rates match closely late Holocene rates of sea-level rise until ~600 YBP; rates increase sharply during the past several hundred years. Sedimentation rates at Rappahannock Sites A-B differ from Potomac Creek Site C that suggests differential compaction in the larger Potomac River catchment basin.

## DISCUSSION

### Paleoenvironmental Trends

Ellison and Nichols (1976) documented vertical zonation of foraminifera along a transect extending from the lowest low water-to highest high water positions at nearby Belle Isle on the Rappahannock River. Following this ecological model, we identify three primary foraminiferal assemblages (Figs. 5, 6) that includes an upland thecamoebian assemblage, a low-to high marsh *Ammoastuta salsa* and *Miliammina fusca* assemblage, and an estuarine *Ammobaculites* spp. assemblage (e.g., Ellison 1972). The grey clay facies of the Potomac Creek core (Figs. 2, 3) records an initial deep central estuarine environment with deposition of clay in association with the *Ammobaculites* assemblage (Figs. 2, 3). The overlying peat and clay facies contain abundant *Ammoastuta salsa* and *Miliammina fusca* that is consistent with peat accumulation that was likely influenced by differential compaction due to autogenic fluvial processes. The uppermost marsh deposits contain abundant macerated plant detritus and *in situ* roots from the plant *Phragmites*. Foraminiferal abundances in the uppermost sediments are low (no. < 10) and thecamoebians are relatively abundant which records the recent development of an upland, freshwater marsh. Ellison and Nichols (1976) also reported foraminiferal trends and radiocarbon results from nearby Hunter Marsh on the Rappahannock River that indicates an approximate uncorrected

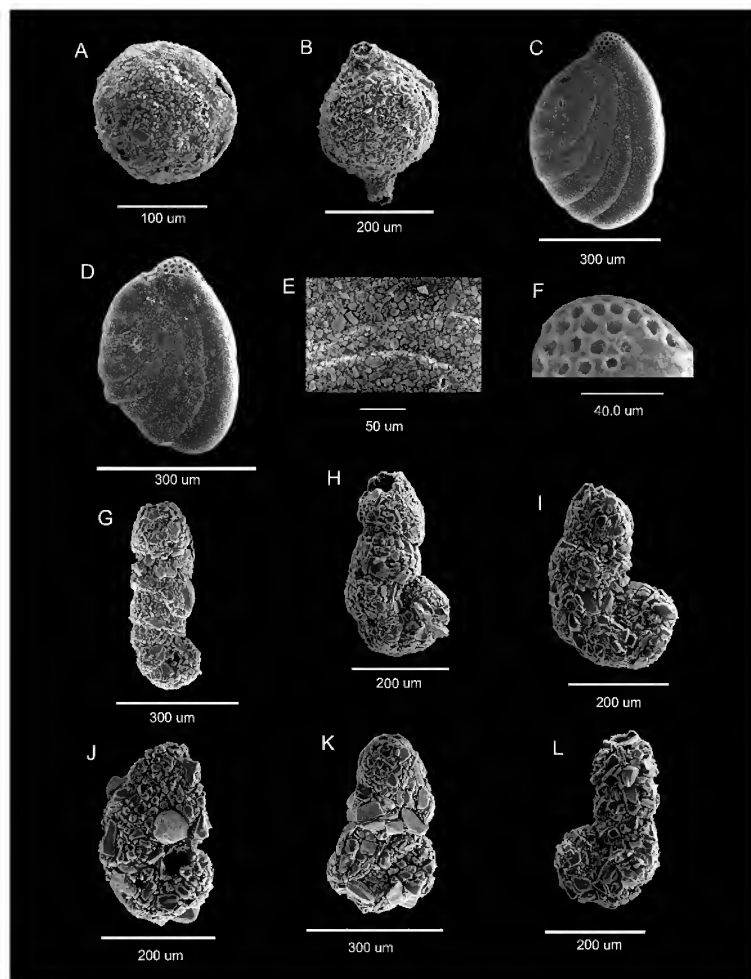


FIGURE 5. Agglutinated foraminifera and thecamoebians from Potomac Creek, Virginia (Site C). A-B. *Arcellacea* sp.; C-F. *Ammoastuta salsa* Cushman and Brönniman; G. *Ammobaculites crassus* Warren; H-K. *Ammobaculites dilatatus* Cushman and Brönnimann; L. *Ammobaculites exiguus* Cushman and Brönnimann.

$^{14}\text{C}$  age of 5780 ybp at the base of the core (9.22 m). Their biotic synthesis was that the fossil populations of the foraminifera changed from domination of open bay (more saline species) to less saline species (freshwater) up core. Considering this previous study and the trends reported herein, we interpret the sedimentary bay-filling sequence in the tidal reaches of the Northern Neck as a product of gradual and steady Holocene sea-level rise with both regional and global processes impacting sedimentation rates as discussed below.

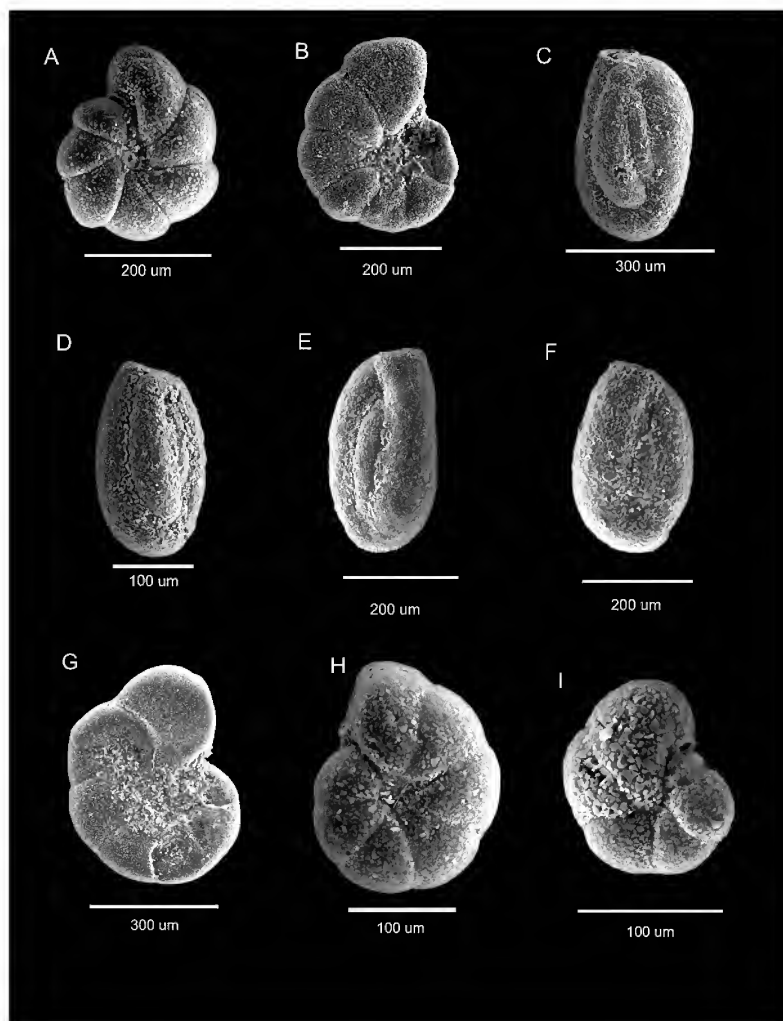


FIGURE 6. Agglutinated foraminifera from Potomac Creek, Virginia (Site C). A, I. *Haplophragmoides manilaensis* Andersen; B, G. *Jadammina macrescens* Brady; C-F. *Miliammina fusca* Brady; H. *Haplophragmoides wilberti* Andersen.

#### Late Holocene Compaction & Subsidence

The Chesapeake Bay region (Salisbury Embayment) is generally regarded as tectonically stable sedimentary basin (Mixon and others 1989) and should therefore be an ideal region to establish sea level baselines for global comparison. Microtidal marshes like those in the Chesapeake Bay region are also thought to present the highest potential for precise sea level predictions (Barlow and others 2013). Accurate predictive models, however, must take into account the role of glacial isostatic

adjustment (GIA) in response to northern hemisphere deglaciation, regional compactional effects, and watershed specific sediment distribution patterns that complicate sea level studies (Barlow and others in press).

Rates for Holocene relative sea level change in nearby coastal Delaware and New Jersey may have been influenced significantly by GIA spanning the past 4000 years (Engelhart and others, 2011). These studies indicate that rates of relative sea-level rise for middle Atlantic marshes are on average higher ( $\sim 1.7 \text{ yr}^{-1}$ ) than the baseline Holocene rate ( $\sim 1.5 \text{ mm yr}^{-1}$ ). Although our results from Potomac River for the past  $\sim 2500$  ybp support this assertion ( $2.96\text{--}4.03 \text{ mm yr}^{-1}$ ), the significantly lower rates at Rappahannock River ( $0.44\text{--}1.50 \text{ mm yr}^{-1}$ ) suggest that differential compaction due to the natural fluvial process might have contributed to the variable, longer term millennial rates of sedimentation in each basin. In this context of regional compaction, Horton and Shennan (2009) estimated that compaction in United Kingdom coastal marshes and estuaries may have contributed to as much  $0.4\text{--}0.6 \text{ mm yr}^{-1}$ , especially in the larger estuaries. The geographically large size of the Potomac River catchment basin, therefore, may have supplied a higher volume of sediment and in due course a higher rate of compaction due to sediment loading.

#### Late Holocene Climate Change

There is reasonable evidence to speculate that late Holocene temperature variability contributed to the abrupt environmental shift from estuarine clay to marsh peat and clay recorded in all cores between  $\sim 1500\text{--}800$  ybp time interval. The Medieval Warm Period (MWP) has been reported from the main axis of the Chesapeake Bay as a relatively strong warmth signal that includes MWP I ( $1600\text{--}1100$  ybp) and MWP II ( $1000\text{--}700$  ybp) (Willard and others 2003; Cronin and others 2003, 2005, 2010). The marked change in foraminiferal assemblages from estuarine (*Ammobaculites* spp.) to marsh (*Ammoastuta salsa*) at Potomac Creek (Fig. 7) indicates a potential base level change on the order a meter or more that superimposed the late Holocene record for the middle Atlantic region (Engelhart and others 2011). The associated increased atmospheric warmth and humidity during the MWP maxima potentially contributed to the transgressive facies shift from grey clay to peat. With respect to 20th century climatic variability, Cronin and others (2005, 2010) have documented decadal and centennial intervals of extended warmth and humidity for the late 19th and 20th centuries that exceed the Medieval Warm Period by as much as  $2\text{--}3^\circ\text{C}$ . In North Carolina, rates of relative sea-level rise from marsh records indicate a  $3.0\text{--}3.3 \text{ mm yr}^{-1}$  sea-level rise that has been attributed to increased thermohaline expansion and/or mass loss from the Greenland Ice Sheet due to rising global temperature (Kemp and others 2009). The apparent freshening trends observed in the tidal reaches of the Potomac (Fig. 7) and Rappahannock suggest that regional sedimentary processes forced by climate change are confounding foraminiferal sea level studies in the recent sedimentary record.

#### Post Colonial Landuse History

Instrumental tide-gauge records from the Potomac River at Washington DC (upstream) and Colonial Beach (downstream) yield relative sea level values of  $3.16 \pm 0.35$  and  $4.78 \pm 1.21 \text{ mm yr}^{-1}$  respectively (NOAA 2009; Boon 2012) (Fig. 1, 5) (Tables 1, 2). Most studies clearly show that the rates of sedimentation for the Chesapeake Bay have increased significantly since initial European land clearance in

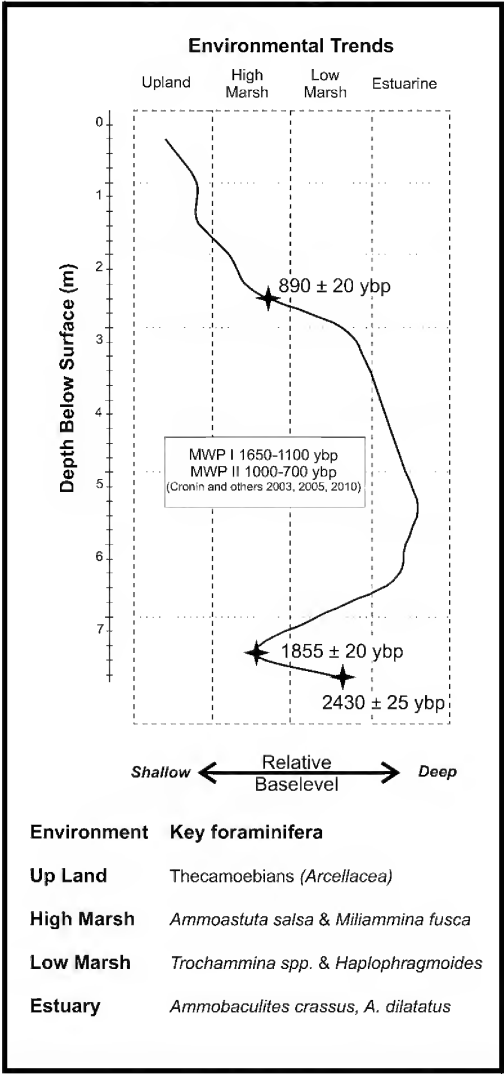


FIGURE 7. A simplified model to demonstrate the past ~2500 years of relative base level change at Potomac Creek. The onset of peat accumulation was preceded by a brief rapid rise in sea level that was broadly synchronous with the timing of Medieval Warm Period climate events recorded in adjacent Chesapeake Bay cores (Cronin and others 2003, 2005, 2010).

1760 CE (Cooper and Brush 1991, 1993; Colman and Bratton 2003). During the past 400 years, humans have altered the watershed of the Chesapeake Bay, by clearing land and creating impervious drainage surfaces that increase runoff, which ultimately increases erosion. A high abundance of fresh water thecamoebians and low abundances

of foraminifera living in the modern marshes support this assertion. Consequently, the higher sedimentation rates observed in the uppermost sediments of all cores are attributed to increased erosion resulting from anthropogenic land use modification in the Rappahannock and Potomac watersheds. Our results indicate that localized sediment loading and regional compactional processes may have contributed to the apparent rates of accelerated rates of sea-level rise for the middle Atlantic region during the late 19th century (Kemp and others 2009, 2011; Tibert and others in press). The anthropogenic loading combined with the predicted increased humidity due to global warming combined with anomalous rate of sea-level rise could potentially exacerbate the coastal erosion problem in the Virginia tidewater region.

### CONCLUSIONS

Marsh cores from tidal reaches along the shores of the historic Northern Neck region of Virginia record a complex sedimentation history for the past ~2500 years. We highlight five major sedimentological and paleoenvironmental trends as follows:

1. Grey clay rich with estuarine foraminifera (*Ammobaculites* spp.) characterize the basal facies in the marsh cores (~4-7 m);
2. Alternating peat and grey clay associated with marsh foraminifera (*Miliammina fusca* and *Ammonia* spp.) characterize the upper intervals of the cores (~1-4 m);
3. The uppermost rooted zones (~0.5 m) are dominated by freshwater grass *Phragmites* and microfossil populations dominated by freshwater thecamoebians;
4. The discordance in the ages observed at the base of the cores in the Rappahannock River and Potomac River marshes indicates that autogenic compactional processes have contributed to the variable rates of sedimentation during the past ~2500 ybp;
5. The sharp increase in sedimentation rates and upward freshening environmental trends at the top of the cores indicate that the combined influences of anthropogenic land use modification and climate change have contributed to high sediment volumes, increased freshwater influx and salt marsh deterioration, and variable fluvial compaction in the proximal tributaries of the Chesapeake Bay.

The high rates of sedimentation and patterns of deposition in the Potomac and Rappahannock region underscore the potential for significant coastal erosion and land management problems with the threat of further sea-level rise in the decades to come.

### ACKNOWLEDGEMENTS

The research presented herein is the result of senior theses completed by student authors SM and JK completed at the University of Mary Washington. We'd like to thank Molly Barber, Drew Uglow, Nate Winston, Fila Baliwag, and Olivia Cooper for their contributions to this data set. We acknowledge financial support provided by the University of Mary Washington with Faculty Development Grants awarded to NET and Undergraduate Research Grants awarded to SM, JK, and LJW. A special thanks to Joe Cutry and his crew at the UMW Auto Shop who helped us maintain safe operational

conditions on the UMW research boat. Thanks to Tom Cronin (USGS) and an anonymous reviewer for their constructive reviews that helped us to greatly improve an early version of this manuscript.

#### ABBREVIATED TAXONOMY

*Ammoastuta salsa* Cushman and Brönnimann 1948

Figure 5 C, D, E, F

*Ammoastuta salsa* (Cushman and Brönnimann) 1948, p.17, pl. 3. – ELLISON and NICHOLS 1970, p. 15, pl. 2, fig. 3.

Remarks: *Ammoastuta salsa* has elongate chambers whereas the later formed chambers increase in size progressively. *Ammoastuta salsa* has a distinct aperture consisting of numerous perforated openings.

*Ammobaculites crassus* Warren 1957

Figure 5 G

*Ammobaculites crassus* WARREN 1957, p. 32, pl. 3, figs. 5,6,7. – ELLISON and NICHOLS 1970, p. 15, pl. 2, fig. 4.

Remarks: *Ammobaculites crassus* has a large test with progressively increased inflation of the chambers. The terminal aperture is large and circular.

*Ammobaculites dilatatus* Cushman and Brönnimann 1948

Figure 5 I, H, K

*Ammobaculites dilatatus* CUSHMAN and BRÖNNIMANN 1948, p.39, pl. 7, figs. 3, 4.

*Ammobaculites cf. A. dilatatus* Cushman and Brönnimann. – ELLISON and NICHOLS 1970, p. 15, pl. 2, fig. 5.

Remarks: *Ammobaculites dilatatus* has a compressed test with 2 or 3 chamber s in a serial array. The final chamber is truncated in appearance a terminal aperture.

*Ammobaculites exiguus* Cushman and Brönnimann 1948

Figure 5 L

*Ammobaculites exiguus* CUSHMAN and BRÖNNIMANN 1948, p.38, pl. 7, figs. 7, 8.

*Ammobaculites cf. A. exiguus* Cushman and Brönnimann. – ELLISON and NICHOLS 1970, p. 15, pl. 2, fig. 6.

Remarks: *Ammobaculites exiguus* has a broad initial coil region that uncoils into a parallel and even uniserial array. The chambers and sutures are relatively indistinct with a terminal aperture that is small and circular.



***Haplophragmoides manilaensis*** Andersen 1953

Figure 6 A, I

*Haplophragmoides manilaensis* ANDERSEN 1953, p. 22, pl. 4, fig. 8. – ELLISON and NICHOLS 1970, p.16, pl. 1, fig. 6. – SCOTT AND OTHERS 1991, pp. 385, pl. 1, figs. 18, 19.

Remarks: *Haplophragmoides manilaensis* has a small, deep umbilicus with inflated chambers that increase in size with growth. Sutures are etched deeply, straight, and protrude in a radial direction outward from the center. An elongate aperture is located below a rim-like protrusion on the terminal chamber.

***Haplophragmoides wilberti*** Andersen 1953

Figure 6 H

*Haplophragmoides wilberti* ANDERSEN 1953, p. 21, pl. 4, fig. 7. – ELLISON and NICHOLS 1970, p.16, pl. 1, fig. 7.

Remarks: *Haplophragmoides wilberti* has slightly inflated chambers with tight, planispiral coiling. Sutures are straight to slightly sigmoidal.

***Miliammina fusca*** (Brady 1870)

Figure 6 C, D, E, F

*Quinqueloculina fusca* BRADY 1870, p. 47, pl. 11, figs. 2, 3

*Miliammina fusca* (Brady). SCOTT and others 1991, pp. 386, pl. 1, fig. 14. – ELLISON and NICHOLS 1970, p.16, pl. 1, fig. 4. – SCOTT and MEDIOLI 1980, p. 40, pl. 2, figs. 1-3.

Remarks: *Miliammina fusca* has elongate chambers that vary in size. The aperture is located at the terminal end of the final chamber.

***Trochammina inflata*** (Montagu 1808)

*Nautilus inflata* MONTAGU 1808, p. 81, pl. 18, fig. 3.

*Trochammina inflata* (Montagu) – SCOTT and others 1991, pp. 388, pl. 2, figs. 7, 8. – ELLISON and NICHOLS 1970, p.16, pl. 1, figs. 8, 9. – SCOTT and MEDIOLI 1980, p. 44, pl. 4, figs. 1-3.

Remarks: *Trochammina inflata* is a relatively large and robust trochospiral taxon with prominent inflation of the chambers.

***Jadammina macrescens*** (Brady 1870)

Figure 6 B, G

*Trochammina inflata* (Montagu) var. *macrescens* BRADY 1870, p. 290, pl. 11, figs. 5a-c.

*Jadammina polystoma* BARTENSTEIN and BRAND 1938, p. 381, figs. 1a-c, 2a-1.  
*Trochammina macrescens* Brady. – ELLISON and NICHOLS 1970, pp.14, pl. 1, figs. 10, 11. – SCOTT and MEDIOLI 1980a, p. 44, pl. 3, figs. 1-8.  
*Jadammina macrescens* Brady. – SCOTT and others 1991, pp. 388, pl. 2, figs. 10, 11.

Remarks: *Jadammina macrescens* has a thin, trochospiral test with numerous pores in the terminal aperture.

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## **A Centennial Record of Paleosalinity Change in the Tidal Reaches of the Potomac and Rappahannock Rivers, Tributaries to Chesapeake Bay**

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### **ABSTRACT**

Gravity and push cores from the Potomac and Rappahannock Rivers (Virginia Tidewater) were collected from central and proximal estuarine zones with known seasonal salinity stratification. The lowermost microfossil associations in the cores comprise alternating ostracode populations of *Cyprideis salebrosa* and *Cytheromorpha*. This microfossil association gives way to an oligohaline association dominated by the freshwater ostracode *Darwinula stvensoni*. Stable oxygen isotope values ( $\delta^{18}\text{O}$ ) of Rappahannock *Cyprideis salebrosa* are highly variable ranging between -6.6 to -3.2‰ VPDB.  $\delta^{18}\text{O}$  values for Potomac *Cytheromorpha fuscata* range from -8.2 to -3.2‰ VPDB. Positive excursions in  $\delta^{18}\text{O}$  values are synchronous with population peaks for both *Cyprideis* and *Cytheromorpha* indicative of increased marine influence and/or higher salinities. Microfossil paleoecology coupled with oxygen isotope values record a marked shift towards gradual freshening and deterioration of the salinity structure in the tidal tributaries during the mid-to late 19<sup>th</sup> century. We attribute these trends to both decadal climate trends and aggressive land use practices in the Chesapeake Bay watershed during the late 19<sup>th</sup> to middle 20<sup>th</sup> centuries.

### **INTRODUCTION**

Estuaries are physically, chemically, and biologically complex environments at the convergence of continental and marine processes. In the Chesapeake Bay, the recent combination of anthropogenic watershed modification and sea-level rise are forcing mechanisms that have potentially influenced mixing of fresh and marine waters in the tidal reaches of the major tributaries (Colman and Bratton 2003; Boon 2012). To test this hypothesis, sediment cores were collected from the proximal and central reaches

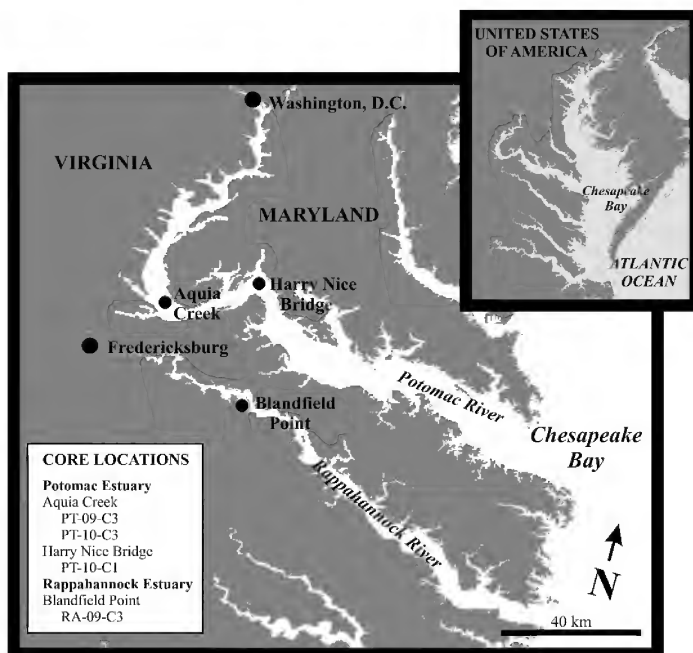


FIGURE 1. Sediment cores were collected from the Potomac and Rappahannock estuaries, both of which are tributaries to Chesapeake Bay, the largest estuary in the eastern United States (Colman and Mixon, 1988).

of the Potomac and Rappahannock estuaries for microfossil and stable isotopic analyses. Paleosalinity indicators were established on the basis of ostracode paleoecology (population abundances and pore morphometrics) and oxygen isotope values ( $\delta^{18}\text{O}$ ). The paleosalinity trends were considered in the context of sedimentation history based on  $^{137}\text{Cs}$  dating, organic matter concentrations, and magnetic susceptibility of collected cores. Cumulative results of these analyses indicate that salinity gradients in both estuaries have changed markedly since the beginning of the 19<sup>th</sup> century which is suggestive of anthropogenic influence on estuarine processes in the Chesapeake Bay.

## BACKGROUND

### Geographic Location

The Chesapeake Bay is the largest estuarine system in the United States that is located between Virginia and Maryland on the Atlantic Coastal Plain (Colman and Mixon 1988). This study focuses on the upper tidal reaches of the Potomac and Rappahannock Rivers where they transition from estuarine-to fluvial conditions (Fig. 1). Sediment cores were collected near the boundary between proximal (oligohaline) and central estuary (mesohaline) near Aquia Creek in the Potomac estuary and Blandfield Point in the Rappahannock estuary (Ellison and Nichols 1970, 1976; Ellison 1972; USEPA 1998). Since the 1980s, these estuaries have produced the highest annual



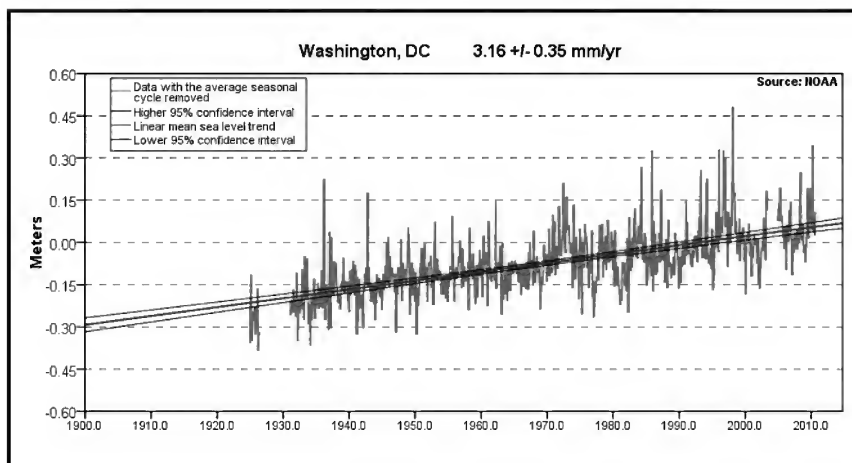


FIGURE 2. Historic sea level data for Washington, D.C. illustrates a constant rise in sea level over the last century for the Potomac estuary (NOAA 2008).

sediment yields for all major Chesapeake Bay tributaries (Langland and Cronin 2003). In general, the relatively high sedimentation rates in Chesapeake Bay are related to ongoing sea-level rise and anthropogenic watershed modification (Fig. 2) (Colman and Mixon 1988; Brush 1989; Colman and Bratton 2003; Boon and others 2010; Boon 2012).

#### Estuarine Circulation

The convergence of fluvial and marine waters creates a dynamic circulation pattern that impacts sedimentary processes in estuarine environments. Where freshwater outflow meets incoming saltwater in a partially mixed estuary like the Chesapeake Bay, the seasonal halocline (salinity gradient) forms a relatively impermeable surface to sediment transport that frequently coincides with the estuarine turbidity maximum (ETM) (Langland and Cronin 2003). In the Potomac estuary, the maximum extent of saltwater intrusion occurs near Aquia Creek (Elliott 1976). In the Rappahannock estuary, the maximum extent of saltwater intrusion occurs near Blandfield Point (Ellison and Nichols 1970). Our preliminary assessment of modern salinity structure revealed oligohaline conditions and/or weak haloclines near Aquia Creek and Blandfield Point during June 2009 (Fig. 3).

#### Microfossils

Ostracodes are aquatic crustaceans that are sensitive to changes in salinity and temperature (Frenzel and Boomer 2005) and their ecological associations have been used to make inferences about past environmental conditions in the Chesapeake Bay (Elliott and others 1966; Cronin and Grinbaum 1999; Cronin and others 2005, 2010). When used in conjunction with  $\delta^{18}\text{O}$  values of their calcite carapaces, ostracodes can be used to develop paleosalinity proxies in the context of both climate induced evaporation and mixing of marine and freshwaters (Anderson and Arthur 1983; Anadón

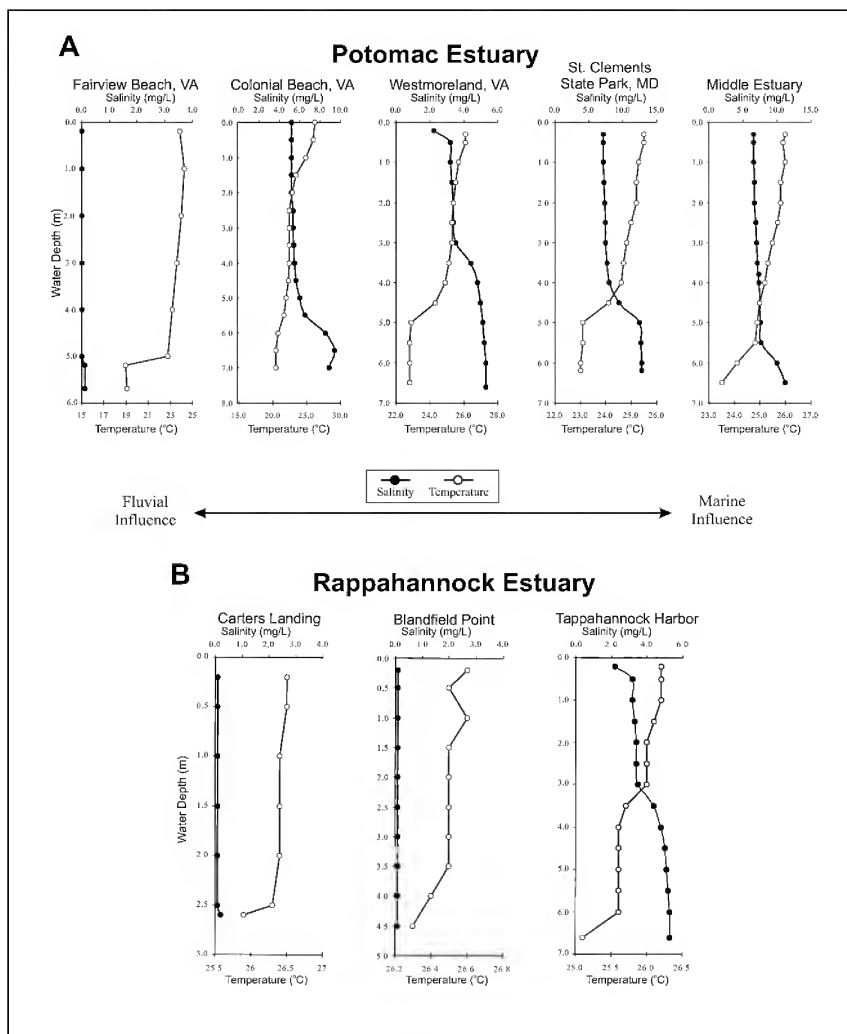


FIGURE 3. Late spring salinity (mg/L) and temperature (°C) profiles measured from the (A) Potomac and (B) Rappahannock estuaries. This analysis was part of an unpublished assessment of water quality during June 2009.

and others 2002; Holmes and Chivas 2002; Ito and others 2003). Studies by Medley and others (2008) demonstrated that the shape of the sieve pores on the external surface of the carapace (Type C of Puri 1974) varies significantly with salinity which further improves the potential for past salinity determinations using ostracoda.

## METHODS

Sediment cores were collected from the Rappahannock and Potomac estuaries with Ogeechee and Gravity (Wildco Inc.) corers (Fig. 1). The longer Ogeechee cores (>100

cm) were analyzed with a Bartington MS2C Core Logging Sensor, and subsequently partitioned into 1 cm segments for loss on ignition and microfossil processing. The shorter gravity cores (40 cm) were divided into 2 cm segments and samples sent to Core Scientific International (Winnipeg, MB, Canada) for  $^{137}\text{Cs}$  analysis *via* gamma spectrometry.

Microfossil census counts were completed at 2 cm intervals using the methods outlined in Medley and others (2008). Sediment samples were rinsed on a 125  $\mu\text{m}$  mesh sieve and wet samples were examined with a stereoscopic zoom microscope (Nikon SMZ1500). Select ostracodes were photographed using a variable pressure scanning electron microscope (Hitachi S-3400N). Morphometric shape analysis was completed according to the methods described by Medley and others (2008). Sieve pores on external valves of *Cyprideis* were traced to determine the areas and shapes using *ImageJ 1.3.1v* (National Institutes of Health by Wayne Rasband). Values for circularity were calculated using the following formula:  $\text{Circularity} = 4\pi (\text{area/perimeter}^2)$ . The best-fit trendline of circularity versus area crossplots was used to determine the pore slope values.

Ostracode carapaces were bathed in deionized water and sent to the Saskatchewan Isotope Laboratory (Saskatoon, SK, Canada) for oxygen and carbon isotope analysis *via* stable isotope ratio mass spectrometry (SIRMS). SIRMS preparation entails the heating of samples *in vacuo* to dissipate contaminants (e.g. organic matter and water that may influence isotope values) prior to analysis with a Finnigan Kiel-IV carbonate preparation device directly coupled to a Finnigan MAT 253 isotope ratio mass spectrometer. Data is expressed relative to the VPDB scale and calibrated to the NBS-19 standard ( $\delta^{13}\text{C}=1.95\text{‰}$  VPDB;  $\delta^{18}\text{O}=-2.2\text{‰}$  VPDB).

Sediment accumulation rates were determined following the  $^{137}\text{Cs}$  analysis method of Robbins and Edgington (1975). Cesium-137 is a radioactive isotope (half life $\sim$ 30 years) that was released into the atmosphere during nuclear testing and simple gamma spectrometry can measure its concentration in sediment (USEPA 2010). Given that atmospheric levels of  $^{137}\text{Cs}$  peaked in 1963, a sampling site's average sedimentation rate can be calculated using the simple stratigraphic thickness above the peak divided by the time in years since 1963. To ensure accurate gamma spectroscopy results, at least 2 g of sediment were removed from the center of each core segment. Forty samples from two Potomac estuary cores were analyzed by Core Scientific International (Winnipeg, Manitoba). Select samples were pretreated for radiocarbon dating at the University of Pittsburgh following the methods outlined by Abbott and Stafford (1996). AMS  $^{14}\text{C}$  analyses were performed at the University of Arizona's Accelerator Mass Spectrometry Laboratory.

## RESULTS

### Physical Stratigraphy

Core PT-09-C3 from Aquia Creek (Potomac River) comprises 134 cm of dark grey clay with a layer of fine sand in the basal 10 cm (Figs. 1, 4). Magnetic susceptibility values average 38.7 SI Units with a minimum value of 18.7 (124 cm) and a maximum value of 166.7 (134 cm). Total organic matter (TOM) averages 6.59 % with a minimum value of 1.42% (132 cm) and a maximum value of 9.68% (11 cm). The maximum concentration of  $^{137}\text{Cs}$  occurs between the 20-22 cm cored interval (Fig. 5).

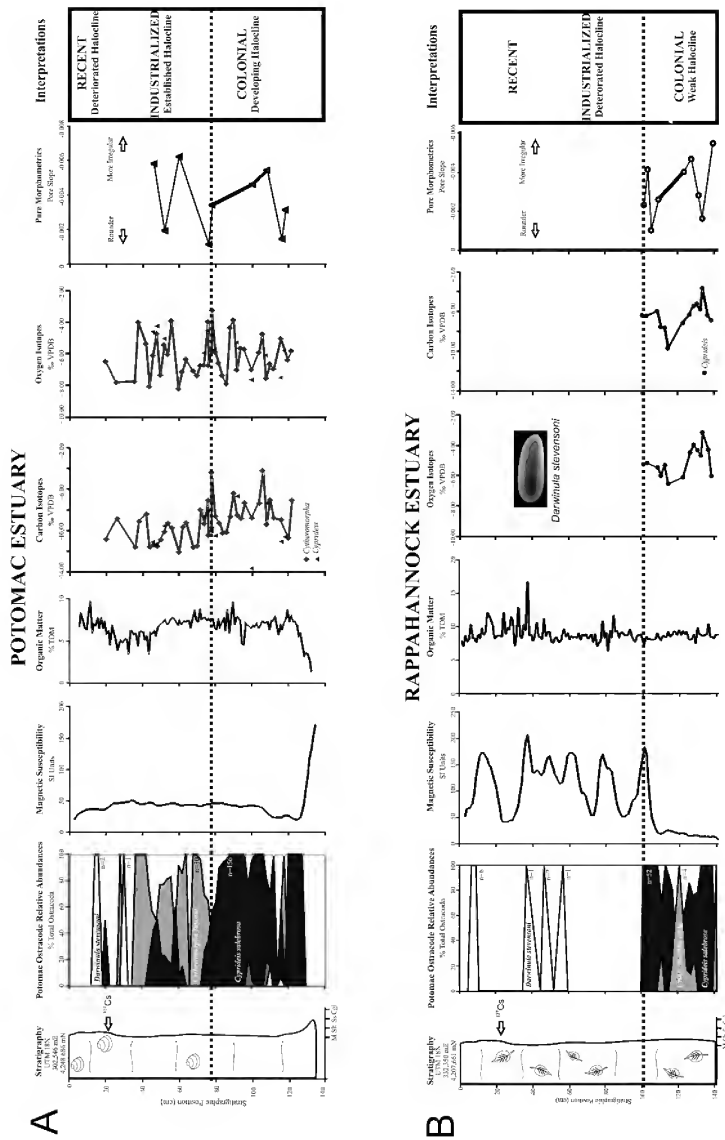


FIGURE 4. (A)Potomac Estuary and (B) Rappahannock Estuary: physical stratigraphy, ostracode populations, magnetic susceptibility, total organic matter, ostracode oxygen isotope values, ostracode carbon isotope values, and *Cyprideis* pore morphometric data. These results are interpreted in the context of three distinct paleosalinity intervals (see Figure 7).

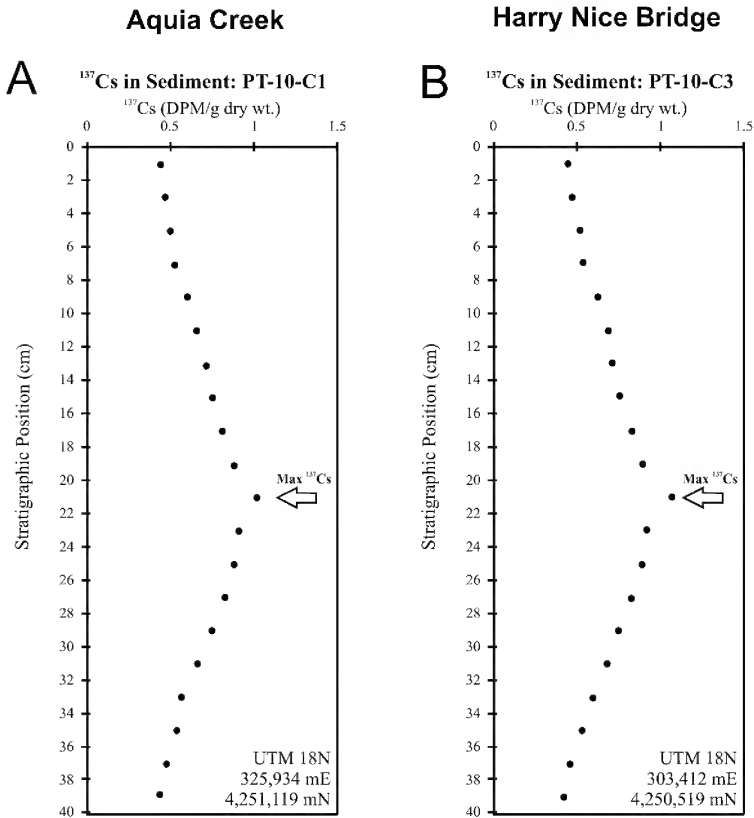


FIGURE 5. Results of  $^{137}\text{Cesium}$  analysis of sediment collected near (A) the Harry Nice Bridge and (B) Aquia Creek.  $^{137}\text{Cs}$  disintegrations per minute (DPM) were greatest between 20 and 22 cm in both cores.

Core RA-09-C3 at Blandfield Point (Rappahannock River) comprises 141 cm of brown-to-grey clay (Figs. 1, 4). Magnetic susceptibility in this core averages 86.3 SI Units with a minimum value of 8.9 (141 cm) and a maximum value of 206.3 (37 cm). Total organic matter averages 8.47% with a minimum value of 6.02% (81 cm) and a maximum value of 16.2% (37 cm). The maximum concentration of  $^{137}\text{Cs}$  occurs between the 20-22 cm cored interval (Fig. 5).

#### Ostracode Paleoecology (Census and Pore Morphometrics)

Ostracodes observed at Aquia Creek include *Cyprideis salebrosa*, *Cytheromorpha fuscata*, and *Darwinula stevensoni* (Figs. 4A, 6). *Cyprideis salebrosa* dominates the 128-20 cm interval with a relative abundance maximum at 84 cm ( $n=146$ ).

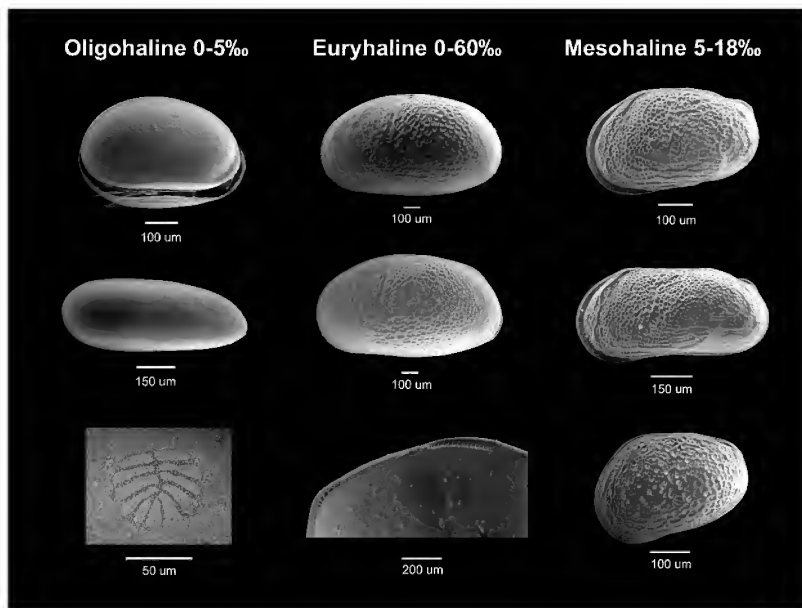


FIGURE 6. Oligohaline (*Darwinula stevensoni*), euryhaline (*Cyprideis salebrosa*), and mesohaline (*Cytheromorpha fuscata* and *Cytheromorpha curta*) ostracodes observed in sediment cores from the Rappahannock and Potomac Rivers. Salinity classification adopted from Belt and others (2005).

*Cytheromorpha fuscata* is relatively common within the 118-20 cm interval with a relative abundance maximum at 70 cm ( $n=30$ ). *Darwinula stevensoni* is sparsely distributed with single valves observed above the 116 cm position (Fig. 4A).

Ostracodes at Blandfield Point include *Cyprideis salebrosa*, *Cytheromorpha curta* and *Darwinula stevensoni*. *Cyprideis salebrosa* is relatively common within the 139-101 cm interval with a relative abundance maximum at 107 cm ( $n=52$ ) (Fig. 4B). *Cytheromorpha curta* is sparsely distributed with relative abundance peaks at 123 cm and 121 cm. *Darwinula stevensoni* is sparsely distributed with occurrences above the 57 cm position (Fig. 4B).

Valves of *Cyprideis salebrosa* from the Potomac River were analyzed for pore morphometric shape at nine stratigraphic positions within the 118-46 cm interval (Fig. 4A). An average of 39 pores were measured per ostracode valve whereas the calculated pore slope values that range from -0.0062 at 60 cm to -0.0011 at 76 cm. Valves of *C. salebrosa* from Blandfield Point (RA-09-C3) were selected for pore analyses at nine stratigraphic positions between 139-101 cm (Fig. 4A). An average of 43 pores were measured per ostracode whereas pore slope values range from -0.0054 at 139 cm to -0.0009 at 105 cm and exhibit a trend toward more positive slope values in the uppermost core.

## Oxygen and Carbon Stable Isotope Values

*Cytheromorpha fuscata*

Oxygen isotope values measured in valves of *Cytheromorpha fuscata* at Aquia Creek average -6.1‰ VPDB. The minimum  $\delta^{18}\text{O}$  value is -8.2‰ VPDB (60 cm) and the maximum value is -3.2‰ VPDB (78 cm) (Table 1)(Fig. 4A).  $\delta^{18}\text{O}$  values are variable with the highest values recorded within the 122-78 cm and 57-38 cm intervals. Values decrease significantly above the 36 cm position.

Carbon isotope values for *C. fuscata* average -9.1‰ VPDB. The minimum  $\delta^{13}\text{C}$  value is -12.0‰ VPDB (60 cm) and the maximum value is -4.2‰ VPDB (106 cm)(Table 1)(Fig. 4A).  $\delta^{13}\text{C}$  values are most positive at the core's base, and gradually decreasing from -7.0 to -12.0‰ VPDB above the 78 cm position. Prominent positive excursion peaks mark the 78 and 106 cm positions (Fig. 4A).

*Cyprideis salebrosa*

Oxygen isotope values of *Cyprideis salebrosa* at Aquia creek average -5.6‰ VPDB. The minimum  $\delta^{18}\text{O}$  value is -7.6‰ VPDB (100 cm) and the maximum value is -4.2‰ VPDB (48 cm) (Table 2)(Fig. 4A).  $\delta^{18}\text{O}$  values of *Cyprideis salebrosa* gradually become higher in the top of the core.  $\delta^{18}\text{O}$  values of *Cyprideis salebrosa* valves from Blandfield Point average -5.1‰ VPDB. The minimum value is -6.6‰ VPDB (115 cm) and the maximum value is -3.2‰ VPDB (134 cm) (Table 3)(Fig. 4B).

Carbon isotope values of *Cyprideis salebrosa* at Aquia Creek are more positive at the base of the core and shift to more negative values above the 78 cm position (Fig. 4A).  $\delta^{13}\text{C}$  values average -9.8‰ VPDB. The minimum value is -13.6‰ VPDB (100 cm) and the maximum value is -6.6‰ VPDB (92 cm) (Table 2) (Fig. 4A).  $\delta^{13}\text{C}$  values at Blandfield Point average -6.4‰ VPDB. The minimum value is -9.7‰ VPDB (115 cm) and the maximum value is -3.6‰ VPDB (134 cm) (Figure 4B). The maxima of both  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  are synchronous with both trending to lower values within the 134-115 cm interval (Table 3) (Fig. 4B).

## Core Geochronology and Sedimentation Rates

Gravity cores (PT-10-C1 and PT-10-C3) collected from the Potomac estuary yield maximum  $^{137}\text{Cs}$  decay rates between 20 and 22 cm that indicates an average sedimentation rate of 0.45 cm/yr since 1963 (Fig. 5). An earlier  $^{137}\text{Cs}$  study at Blandfield Point (Rappahannock River) (Baliwag and others 2010) yielded an average sedimentation rate of the 0.54 cm/yr (see Tibert and others 2013). A single AMS  $^{14}\text{C}$  radiometric date from a core in the Rappahannock River (upstream of Blandfield Point) yielded an uncorrected date of  $245 \pm 15$  that suggests a longer term sedimentation rate of 0.36 cm/yr. The collective summary of the sedimentation rates and the AMS  $^{14}\text{C}$  in the Rappahannock and Potomac Rivers indicates basal core ages that approximate middle-to late 18th century colonial times ( $1767 \pm 15$ ).

## DISCUSSION/INTERPRETATIONS

## Paleosalinity Indicators

Ostracodes reported from the tidal reaches of the Potomac and Rappahannock Rivers have well known ecological tolerances in estuarine environments (Frenzel and Boomer 2005). Species of *Cytheromorpha*, including *C. fuscata* and *C. curta*, are often

TABLE 1. Stable isotope values of *Cytheromorpha* spp. from the Potomac River.

Stratigraphic Position (cm)	$\delta^{18}\text{O}$ (‰ V-PDB)	$\delta^{13}\text{C}$ (‰ V-PDB)
20	-6.46	-10.75
26	-7.80	-8.78
36	-7.75	-11.51
38	-3.98	-9.06
42	-5.34	-8.36
44	-8.05	-11.50
46	-6.08	-11.35
48	-4.70	-11.41
50	-7.35	-10.80
52	-5.42	-10.06
54	-6.02	-9.30
56	-3.90	-9.68
60	-8.19	-12.00
62	-7.16	-9.59
68	-7.09	-11.55
74	-6.69	-9.25
76	-3.94	-7.03
76	-6.73	-10.40
78	-5.74	-9.68
78	-3.22	-4.37
80	-5.86	-8.52
64	-6.32	-9.17
70	-7.38	-11.42
72	-6.74	-7.96
82	-6.57	-9.24



TABLE 1. Continued

Stratigraphic Position (cm)	$\delta^{18}O$ (‰ V-PDB)	$\delta^{13}C$ (‰ V-PDB)
84	-7.38	-10.14
86	-7.86	-10.12
88	-4.32	-8.63
90	-3.83	-6.40
92	-6.97	-8.49
94	-5.61	-8.75
96	-5.69	-7.28
100	-6.99	-8.71
104	-5.90	-7.31
106	-4.47	-4.21
108	-7.53	-9.34
110	-6.62	-6.97
112	-6.93	-8.74
116	-5.04	-8.92
120	-6.35	-10.61
122	-5.79	-7.05

associated with mesohaline conditions (mesohaline = ~7-15 ‰), while *Darwinula stevensoni* is restricted to oligohaline waters (oligohaline = 0-5 ‰)(Elliot and others 1966; Cronin and Vann 2003). *Cyprideis salebroza*, on the other hand, is common in both hyposaline and hypersaline environments, and can therefore has a wide salinity tolerance (euryhaline = 0-60‰)(Sandberg and Plusquellee 1974; Carbonnel 1983).

*Cyprideis salebroza* has been used to reconstruct Holocene paleosalinity histories in lagoonal and lacustrine deposits in the Dominican Republic (Medley and others 2008). This studies show that synchronous positive excursions of the  $\delta^{18}O$  values coupled with increased sieve pore irregularity are viable indicators for times of increased aridity and salinity. Although the  $\delta^{18}O$  values of Potomac River water are more lower than those reported from Lago Enriqueillo (a hydrologically closed lake), they do closely match  $\delta^{18}O$  values of foraminiferal calcite reported in the Chesapeake Bay (Cronin and others 2005). The isotope values considered in the context of sieve shape variability serve as confirmation for significant changes in salinity spanning the past several centuries.

TABLE 2.Stable isotope values of *Cyprideis salebrosa* from the Potomac River.

Stratigraphic Position (cm)	$\delta^{18}\text{O}$ (‰ V-PDB)	$\delta^{13}\text{C}$ (‰ V-PDB)
46	-4.58	-11.05
48	-4.22	-11.21
52	-5.02	-9.49
74	-5.91	-8.56
76	-4.51	-7.99
78	-4.83	-10.01
80	-5.68	-10.43
92	-5.25	-6.60
100	-7.61	-13.57
108	-6.04	-7.26
116	-7.47	-10.99
118	-5.77	-10.51

A Centennial Record of Paleosalinity for the Virginia Tidewater

Basal core intervals in the Potomac River are characterized by euryhaline ostracodes with inconsistent oxygen isotope values that support our interpretation of a highly variable annual salinity range during late colonial times (Fig. 7). Trends in  $\delta^{18}\text{O}$  values reflect the ostracodes’ preference to live close to the landward extent of the marine salt wedge in the partial mixed estuary. Given that this interval pre-dates the industrial period, the seasonal stratification in this partially mixed Chesapeake Bay estuary maintained a salinity gradient that was not significantly impacted by natural storm events.

The middle intervals in the cores exhibit  $\delta^{18}\text{O}$  values that trend toward their maximum values. This pronounced variability in the isotopic variability is coincident with a paleoecological shift to a *Cytheromorpha fuscata*-dominated ostracode association, thus recording the transition from near-oligohaline (~5-10 ‰) to increased mesohaline (~7-15 ‰) salinities. Within this interval,  $\delta^{18}\text{O}$  values vary over 5‰ highlighting the magnitude of the salinity gradient at this time (Fig. 7). The relative abundance of *Cyprideis salebrosa* with irregular pore shapes supports our interpretation for elevated salinities likely due to increasing marine influence due to sea-level rise during the early-late 19<sup>th</sup> century.

The uppermost core intervals show a sharp decline in *Cytheromorpha fuscata* and a marked decrease in  $\delta^{18}\text{O}$  values. Because fresh water has lower  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  values than marine water (Patterson and Walter 1994, Patterson 1998), the lower  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  values of ostracode carapaces were likely forced by a transition to less saline water.

TABLE 3. Stable isotope values of *Cyprideis salebrosa* from the Rappahannock River.

Stratigraphic Position (cm)	$\delta^{18}\text{O}$ (‰ V-PDB)	$\delta^{13}\text{C}$ (‰ V-PDB)
101	-5.25	-6.33
103	-5.17	-6.39
109	-5.48	-5.93
111	-5.98	-7.51
113	-5.34	-7.60
115	-6.55	-9.67
123	-6.12	-7.13
127	-4.47	-6.28
129	-3.98	-5.44
131	-4.32	-5.20
133	-4.66	-5.73
134	-3.18	-3.62
137	-4.30	-6.31
139	-6.02	-6.84

Sedimentation rates during this interval indicate an average rate of 0.45 cm/yr that also corresponds to a paleoecological shift to the freshwater ostracode *Darwinula stevensoni*. Population shifts, pore shape analyses, and isotope trends indicate decreased salinity and weakening salinity gradient near Aquia Creek during the early 20<sup>th</sup> century (Figs. 4, 7).

#### Climate Forcing and Sediment Loading

Cronin and others (2005) evaluated oxygen and carbon isotopes from calcareous foraminifera, and magnesium-calcium ratios from ostracode carapaces that generally oscillate in-phase for the last ~150 years in the Chesapeake Bay. Similar in-phase variations characterize the isotope record from Rappahannock and Potomac ostracodes (e.g.,  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  maxima at 78 cm) (Fig. 4). The variability in our paleosalinity proxy indicators suggests that global climatic events, including the last vestiges of the Little Ice Age (Cronin and others 2003), may have influenced late 18<sup>th</sup> and early 19<sup>th</sup> century salinity variability in both the Rappahannock and Potomac estuaries. Cronin and Vann (2003) and Cronin and others (2005, 2010) analyzed ostracode and foraminifera populations collected from the mouth of the Patuxent estuary. Their results indicate that decadal climate variability in the Chesapeake Bay is potentially influenced by the

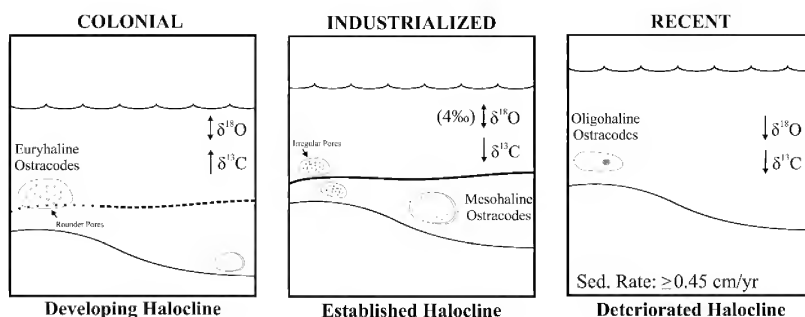


FIGURE 7. Model of paleosalinity change in based on microfossil populations, geochemistry, and stratigraphy of the Potomac estuary, and supported by supplementary results from the Rappahannock estuary. Three stages of halocline (A) development/strengthening, (B) establishment, and (C) deterioration were reconstructed for the last two centuries in the tidal reaches of these estuaries.

North Atlantic Oscillation and possibly El Niño Southern Oscillation (ENSO). The apparent decadal variability in our paleosalinity data substantiates their hypothesis.

Between 1983 and 2000, the Rappahannock and Potomac Rivers produced the greatest average annual sediment yields for all major Chesapeake Bay tributaries (Langland and Cronin 2003). Sedimentation rates and patterns are variable across the bay due to its tributaries' variable physiographic identities and land use histories (Brush 1989; Langland and Cronin 2003). Brush (1989) linked recently altered sedimentation rates and patterns in Chesapeake Bay tributaries to aggressive post-colonial land development. However, the amount of this "legacy sediment" stored in Chesapeake Bay watersheds, as well as time required for it to reach the bay, currently remains unquantified (Langland and Cronin 2003).

## CONCLUSIONS

The paleosalinity history for the Potomac and Rappahannock Rivers is likely related to both natural climate change and anthropogenic forcing mechanisms. The initial shift from euryhaline-to mesohaline dominated ostracode associations was attributed to increasing salinity associated with ongoing Holocene sea-level rise. Despite the increasing marine influence due sea-level rise, sediment deposited in the tidal reaches during the 20<sup>th</sup> century was characterized by increased abundances of oligohaline ostracodes with decreasing  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  values. While the exact cause of decreasing salinity during a period of 20th century is unknown, our results corroborates the hypothesis that anthropogenically-induced salinity change, post-Industrial times, has had a significant impact on seasonal salinity gradient development in the tidal reaches of the Potomac and Rappahannock Rivers.

## ACKNOWLEDGEMENTS

The research presented herein is the result of a senior theses completed by student author LJW completed at the University of Mary Washington. We'd like to thank

Olivia Cooper, Nate Winston, Fila Baliwag, and Henry Talley for their contributions to this data set. We acknowledge financial support provided by the University of Mary Washington with Faculty Development Grants awarded to NET and Undergraduate Research Grants awarded to LIW, ORC, and HT. The UMW Summer Science Institute provided funding to LJW and EJ to support their research during the summer of 2009. We also would like to thank Dr. Ben Kisila (UMW) for his help with  $^{137}\text{Cs}$  methodologies and the many discussions regarding the sedimentation history for our sites. Thanks to Dinka Besic at the Saskatchewan Isotope Laboratory for loading and analyzing samples for stable isotope values. A special thanks to Joe Cutry and his crew at the UMW Auto Shop who helped us maintain safe and operational conditions on the UMW research boat. Thanks to the anonymous reviewers for their thoughtful comments that helped to improve the final version of this manuscript.

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## Camera Trap Success Among Carnivores and Prey Animals in Tazewell County, Virginia

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### ABSTRACT

Obtaining basic ecological information on occurrence and activity levels in cryptic and elusive species is often difficult. Camera trapping provides a relatively inexpensive opportunity to acquire such data. We used infrared-triggered cameras to assess trap success and activity levels of several species across four consecutive seasons, including: *Ursus americanus* (black bear), *Lynx rufus* (bobcat), *Canis latrans* (coyote), *Vulpes vulpes* (red fox), *Urocyon cinereoargenteus* (gray fox), *Procyon lotor* (raccoon), *Odocoileus virginianus* (white-tailed deer), *Didelphis virginiana* (opossum), *Sciurus carolinensis* (gray squirrel), and *Meleagris gallopavo* (wild turkey). With a total of 396 trap nights (TN) at one station over the span of four consecutive seasons, overall trap success rate was 86.87 captures per 100 TN. Trap success was highest in wild turkeys (31.57/100 TN), followed by raccoons (15.66/100 TN), gray squirrels (10.86/100 TN), gray foxes (8.59/100 TN), white-tailed deer (8.08/100 TN), opossums (5.56/100 TN), coyotes (1.52/100 TN), red foxes (1.26/100 TN), and bobcats (0.76/100 TN). Overall trap success significantly varied across all target species combined (Kruskal Wallis Chi-Square = 349, d.f. = 10,  $p < 0.0001$ ). However, trap success did not vary across all seasons for all target species combined (Kruskal Wallis Chi-Square = 0.99, d.f. = 3,  $p = 0.78$ ). This study is the first to use camera trapping to examine species presence and activity levels in a longitudinal manner for cryptic and elusive species of southwest Virginia.

### INTRODUCTION

Camera trapping is an excellent non-invasive tool for identifying cryptic or elusive species (Yasuda, 2004; Rowcliffe et al. 2008). While this approach to elusive species identification is not a recent revelation in ecological methodologies (e.g., Chapman, 1927), camera trap usage has picked up momentum in recent years (Karanth and Nichols, 1998). In fact, published papers utilizing some degree of camera trapping have seen an estimated 50% annual growth over the past decade (Rowcliffe and Carbone,

2008). Much of this growth can be attributed to increased technological and analytical advances that allow ecologists to determine population densities, dispersal behaviors, and relative abundance – all from a distance (Karanth and Nichols, 2000; Kelly et al. 2012).

Trap success is one common index of activity level that can be obtained using camera trap data. Trap success calculated per species can provide insight into species presence or, at a more interactive scale, potential species interactions among predators/prey (Kelly and Holub, 2008), despite recent debate about its use as an index of abundance (Anderson, 2003; O'Brien et al., 2003). Regardless of debate, it is impractical to ignore the importance of understanding predator/prey dynamics particularly in the wake of increasing anthropogenic disturbances that are altering natural community composition and interactions (Sala et al., 2000; Walker et al., 2005). Thus, the value of camera trapping becomes magnified for elusive species that act as predators and/or prey in their respective systems. Such value is further magnified when camera trapping is employed in highly understudied locations, such as Virginia, in order to elucidate cryptic species interactions.

Our study used camera trapping to survey medium to large-sized mammalian and terrestrial avian species known to occur at our study site. Specifically, we targeted *Ursus americanus* (black bear), *Lynx rufus* (bobcat), *Canis latrans* (coyote), *Vulpes vulpes* (red fox), *Urocyon cinereoargenteus* (gray fox), *Procyon lotor* (raccoon), *Odocoileus virginianus* (white-tailed deer), *Didelphis virginiana* (opossum), *Sciurus carolinensis* (gray squirrel), and *Meleagris gallopavo* (wild turkey). We report overall and seasonal trap success for each target species in the understudied state of Virginia.

## MATERIALS AND METHODS

Our study site was located on private property in Tazewell County, near the town of Richlands, Virginia (Fig. 1). The site is situated at approximately 615 m in elevation within a mostly deciduous forest. Trap camera location (one station) was along a fence that bisected a north-facing forested hillside consisting of predominately yellow poplar (*Liriodendron tulipifera*). However, northern red oak (*Quercus rubra*), white oak (*Q. alba*), American ash (*Fraxinus americana*), and eastern red cedar (*Juniperus virginiana*) were also in the adjacent area. Cameras were mounted approximately 80 cm above the ground in a location that would funnel animals in the pathway of the lens that was approximately 3 m away.

Two types of cameras were used throughout the duration of this study: a StealthCam MC2-G and a DeerCam 200, both of which are passive infrared-triggered 35 mm film cameras. These cameras are triggered by heat and motion detectors. The StealthCam MC2-G, programmed with 1 min intervals between each image capture, was used from 1 October 2005 to 25 January 2006. The DeerCam 200, programmed with 15 sec intervals between each image capture, was used from 26 January 2006 until the end of the study. Both cameras, when active separately, were active 24 hours a day. Cameras were routinely checked for basic maintenance and battery and film replacement. No bait or lures were used to attract target species. No camera malfunctions were noted throughout this longitudinal study.

Trap success for each targeted species was calculated as the number of trap events per 100 trap-nights. In order to prevent duplicate counting of images taken over short periods of time (i.e., less than 30 min apart; Kelly, 2003; Silver et al., 2004), date/time

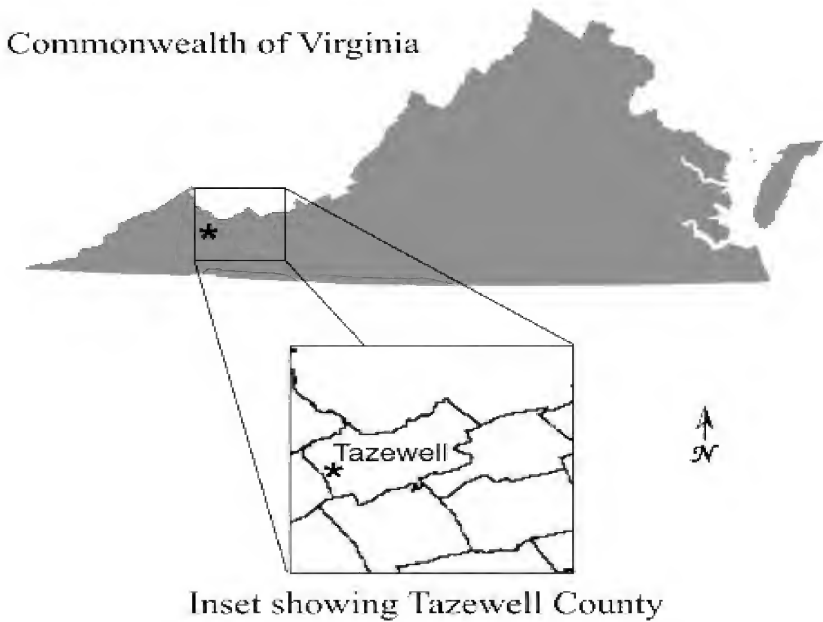


FIGURE 1. Study site location.

stamps on each photograph and individual animal size, position, and markings were examined. Special care was taken to accurately estimate the number of wild turkeys (*M. gallopavo*) for each camera trap event since they periodically appear as a flock that, subsequently, triggered multiple image captures. Because data did not meet assumptions of normality, nonparametric statistical analyses were conducted. Specifically, we used a nonparametric Kruskal-Wallis test to compare overall trap success amongst all targeted species to compare trap success among seasons for each target species. We conducted this study over an entire year, thus all four seasons are represented. Spring season consists of March, April, and May image captures. Summer season reflects image captures from June to August. Fall season includes all image captures from September to November. Finally, winter season includes all image captures from December to February. All statistical analyses were conducted using SAS JMP 9.0 (SAS Institute, Cary, North Carolina).

## RESULTS

In total, we photographed nine species (eight mammals and one bird) without the use of lures or baits. Specifically, six (bobcat, coyote, red fox, gray fox, raccoon, and opossum) are considered to be predatory species while the remaining three (white-tailed deer, gray squirrel, and wild turkey) are considered to be prey. We amassed a total of 396 trap nights (TN) and recorded 344 trap events, with a total of 637 target animal photographs (Table 1). Overall trap success for all animals photographed was 86.87 per

TABLE 1. Total number of trap events, number of animals photographed, and overall trap success.

Species (common name)	Total number of trap events	Total number of photographs
<i>Meleagris gallopavo</i> Linnaeus (wild turkey)	125	237
<i>Procyon lotor</i> Storr (raccoon)	62	87
<i>Sciurus carolinensis</i> Gmelin (gray squirrel)	43	57
<i>Urocyon cinereoargenteus</i> Schreber (gray fox)	34	39
<i>Odocoileus virginianus</i> Zimmerman (white-tailed deer)	32	163
<i>Didelphis virginiana</i> Kerr (opossum)	22	22
<i>Canis latrans</i> Say (coyote)	6	8
<i>Vulpes vulpes</i> Linnaeus (red fox)	5	8
<i>Lynx rufus</i> Schreber (bobcat)	3	4
<i>Ursus americanus</i> Pallas (black bear)	0	0
Unknown	12	12
Grand Total	344	637
Total number of trap nights	396	

100 TN (Table 1). In terms of individual species contributing to successful trap events, the majority of raw photographic events were *M. gallopavo* (wild turkey; 36.34%), followed by *P. lotor* (raccoon; 18.02%), *S. carolinensis* (gray squirrel; 12.5%), *U. cinereoargenteus* (gray fox; 9.88%), *O. virginianus* (white-tailed deer; 9.3%), *D. virginiana* (opossum; 6.4%), *C. latrans* (coyote; 1.74%), *V. vulpes* (red fox; 1.45%), and *L. rufus* (bobcat; 0.87%). No *U. americanus* (black bear) were photographed.

Trap success significantly varied across all targeted animals (Kruskal Wallis Chi-Square = 349, d.f. = 10,  $p < 0.0001$ ) (Fig. 2). Trap success was highest in *M. gallopavo* (wild turkey; 31.57/100 TN). *Procyon lotor* (raccoon; 15.66/100 TN) had the second highest trap success, followed by *S. carolinensis* (gray squirrel; 10.86/100 TN), *U. cinereoargenteus* (gray fox; 8.59/100 TN), *O. virginianus* (white-tailed deer; 8.08/100 TN), *D. virginiana* (opossum; 5.56/100 TN), unknown/unidentifiable photographs due to poor quality (3.03/100 TN), *C. latrans* (coyote; 1.52/100 TN), *V. vulpes* (red fox; 1.26/100 TN), and *L. rufus* (bobcat; 0.76/100 TN). Trap success did not significantly vary across seasons for all targeted species combined (Kruskal Wallis Chi-Square = 0.99, d.f. = 3,  $p = 0.78$ ) (Fig. 3.). Unfortunately, rigorous comparisons of seasonal trap success within each individual targeted species were not possible due to low sample sizes among individual seasons.

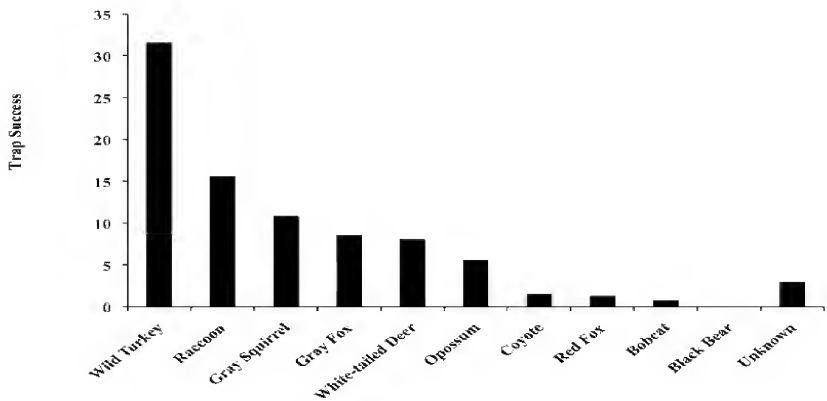


FIGURE 2. Overall trap success for each target species.

DISCUSSION

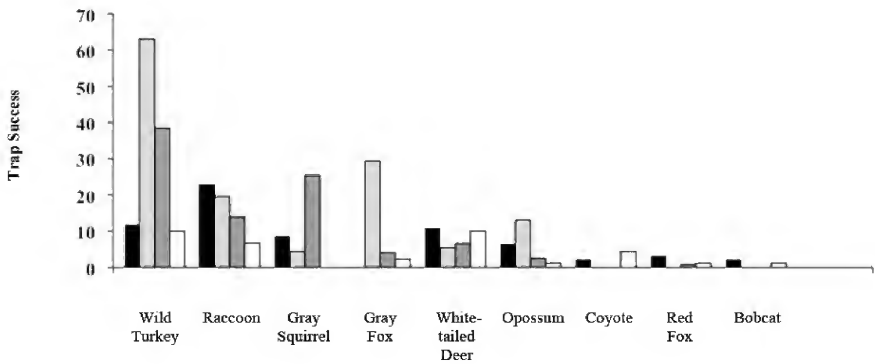


FIGURE 3. Trap success for each target species as a function of season. Spring (black bar) months were March, April, and May. Summer (light gray bar) months were June, July, and August. Fall (dark gray bar) months were Sepetmber, October, and November. Winter (white bar) months were December, January, and February.

While our trap success rates appear low, with most target species having a trap success of less than 10/100 TN, they are reflective of trap success rates reported by other recent studies in North America (Gompper et al., 2006; Kelly and Holub, 2008). Thus, our study adds to the support of utilizing camera traps to address basic ecology questions such as species presence and activity levels.

Interestingly, we did not photograph a single *U. americanus* (black bear). There could be a few possible explanations for this unexpected result. For example, black bears have relatively low reproductive rates, primarily due to their slow reproductive maturation, lengthy reproductive cycle, and small litter sizes (Eiler et al., 1989). Thus,

black bear recruitment is a prolonged process even under ideal environmental conditions. This could account for not capturing a black bear on film since our study duration was only one year. However, anthropogenic disturbances, such as hunting and habitat modification, could potentially decrease already relatively low recruitment rates in black bear populations. Another possible explanation for the lack of capturing black bear images was our methodology. Our study did not employ the use of baits at our study site. Baited camera traps have had great success in capturing black bear images (Martorello et al., 2001). Finally, the lack of photographing black bears could be attributed to our number of trap nights. Some studies have suggested that approximately 1000 trap nights are needed to determine whether a species is truly absent from an area (Carbone et al., 2001). Thus, future studies over a larger geographic area could attempt to ascertain the population status of black bears in southwest Virginia.

In summary, our results support the practice of using camera trapping as a means of assessing the ecology of typically cryptic species. While most camera trapping studies have multiple camera stations, they often lack longitudinal breadth since their durations are typically three months or less. Our study is one of the first to utilize camera trapping over the course of an entire year, thus providing interesting and novel species presence and activity level data across seasons in southwest Virginia. With little investment in terms of time and man-power (Srbek-Araujo and Chiarello, 2005), camera trapping can serve as a powerful tool to assess species presence and activity levels. We plan on continual monitoring of our study site over the next decade in order to collect data for comparative analyses. Increasing the number of trap nights and camera stations over multiple years could provide us with a unique opportunity to statistically caste trends concerning species occurrence, abundance, displacement, predator-prey interactions, and/or predator-predator interactions. Such data could prove to be invaluable to ecologists and conservationists alike.

#### ACKNOWLEDGEMENTS

JAV wishes to thank the Department of Mathematics and Computer Science at the University of Virginia's College at Wise for partial support of this project. Other support for this project was given to DLC by the Department of Biological and Environmental Sciences at Longwood University. We also wish to thank the two anonymous reviewers for providing comments that greatly improved earlier versions of this manuscript.

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# **Exploratory Modeling Indicates Red-Backed Salamander Detections are Sensitive to Soil pH at C. F. Phelps Wildlife Management Area, Virginia**

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## **ABSTRACT**

Red-backed salamanders represent an important component of Virginia ecosystems, but there are few habitat models that can reliably predict the presence/absence of this species. We surveyed the habitats of red-backed salamanders at one site in the Piedmont region of Virginia and collected data on an array of habitat variables with which this species is normally associated. We used logistic regression to develop a model predicting the presence or absence of the species at a given 50m-transect. Our final model incorporated soil organic layer pH variability and mineral layer average pH, and accounted for 30% of the variation in our data. We conclude that soil pH is a limiting determinant of habitat use for this study site, and that it may affect adaptive behaviors for highly acidic soils.

## **INTRODUCTION**

As researchers address the issues of amphibian decline, there is an increasing need to better understand how salamanders in terrestrial ecosystems interact with their habitat. Greater understanding of the habitat ecology of these species would likely improve our ability to manage and conserve amphibian diversity in local watersheds, thereby reducing the ecosystem damage that would result from the loss of these species (Cushman 2005, Wyman 1990).

In the Rappahannock River watershed of Northern Virginia, both Mitchell (1998) and McGhee and Killian (2010) have surveyed amphibian, and specifically, salamander diversity, but little has been done to assess the habitat relationships of commonly detected species. To address this need, we conducted a preliminary study of salamander habitat for a single site in the Rappahannock River drainage at the C. F. Phelps Wildlife Management Area (WMA) concurrent with a species diversity survey and developed a simple habitat model for our most commonly detected terrestrial salamander, *Plethodon cinereus* Green 1818 (red-backed salamander).

The red-backed salamander is common to Virginia forests and the Rappahannock River watershed, and is considered an important component of the local ecosystems in which they occur (Burton and Likens 1975, Davic and Welsh 2004). While several studies have noted particular habitat features associated with this species, such that a hypothetical niche-gestalt can be conceptualized (James 1971), only a few studies have actually developed predictive models of habitat use, primarily to compare the effects of silviculture treatments (Demaynadier and Hunter 1998, Morneau et al. 2004, McKenney et al. 2006).

The red-backed salamander occurs in the leaf-litter and well-drained soil underlying deciduous, northern conifer, and mixed deciduous-coniferous forests with numerous cover objects (logs and rocks) and little underbrush (Burger 1935, Petranks 1998, Richmond and Trombulak 2009). This lungless salamander is dependent on gas exchange through the skin for respiration, and is sensitive to moisture and temperature shifts, typically adjusting to these changes by moving vertically through the soil column (Taub 1961, Heatwole 1962, Spotila 1972). They tend to prefer a neutral soil pH, cooler temperatures and ready access to lower soil layers as predation refugia (Bogert 1952, Heatwole 1962, Spotila 1972, Wyman and Hawksley-Leseault 1987). Females attach eggs within natural crevices or beneath embedded rocks or decaying logs (Petranks 1998).

We wished to determine whether we could successfully predict red-backed salamander occurrence at a given site using variables associated with these general habitat features known to be key components in their ecology. We hypothesized that red-backed salamanders would be detected in leaf litter associated with cover objects and moist, cool soil conditions of neutral pH. We predicted that a logistic regression model would include variables measuring the amount of coverage by cover objects, soil moisture, and soil pH.

## METHODS

We used transect sampling to locate salamanders (Jaeger 1994, Jaeger and Inger 1994, Mitchell 2000). We randomly selected the starting location of transects using a GPS. We sampled transects by searching five 1-m<sup>2</sup> quadrats placed randomly within 10m increments (Jaeger 1994, Jaeger and Inger 1994, Mitchell 2000). We searched quadrats by removing large cover objects (rocks and decaying wood) and searching leaf litter (Mitchell 2000). We identified captured salamanders to species, and measured snout-vent length and total length to estimate and assign age-classes (Petranks 1998, Moore and Wyman 2010).

We collected habitat data at both the transect-level and the quadrat-level. Transect-level data included air temperature, air pressure, relative humidity, vapor pressure deficit (vapor pressure deficit represents the difference between the actual moisture in the air and the amount of moisture the air could hold when saturated at a given temperature: Bellis 1962), degree and direction of slope, general weather (clear, partly cloudy, overcast, light rain, heavy rain), and habitat (coniferous, mixed deciduous, mixed coniferous-deciduous, open-field/*Rosa multiflora* brush). Quadrat-level data included soil pH, soil moisture, soil temperature, leaf litter depth, and percent cover (bare ground, leaf litter, natural cover, ground vegetation, and woody stem).

We determined soil pH and soil moisture of cored soil samples in a laboratory. Soil samples were obtained by taking 31.7 mm diameter soil probe cores from a quadrat

until sufficient soil was obtained to fill two collection tubes (50 mL centrifuge tubes) with separate organic and mineral fractions. In the laboratory each fraction was thoroughly mixed followed by division into two approximately equal parts—one for percent soil moisture and one for pH. Percent soil moisture was determined by massing the wet samples followed by drying for 24 hours in a 50°C oven. Soil pH was determined using a Barnant 20 digital pH meter. The sample (placed in the centrifuge tube) was covered with enough distilled water to keep the pH probe above the sediment. We waited for 20 minutes to allow the more coarse soil particles to settle out. We then measured the pH after the reading stabilized, but not to exceed 1 minute. We measured leaf litter depth using a ruler placed once within a randomly chosen quadrant of the quadrat. We used the Daubenmire (1959) method to estimate ground cover within quadrats.

As we had little information from which to base hypotheses regarding habitat selection at this site, we used logistic regression as an exploratory modeling approach to determine which predictor variables were most associated with captured salamanders at the transect level. For variables measured at the quadrat level, we tested both mean values and their standard deviations as predictors. From our data we created new multiplicative variables where synergistic effects seemed likely (synergistic variable 1: soil temperature\*organic layer soil moisture\*mineral layer soil moisture, synergistic variable 2: organic-layer soil pH\*organic layer soil moisture). We used forward stepwise selection ( $P = 0.05$  to enter and 0.10 to remove) in SPSS (SPSS Inc., Chicago IL). Variable coefficients were assessed using the change in -2 loglikelihood (Hosmer and Lemeshow 1989). The explanatory value of the selected model was evaluated using Nagelkerke's  $r^2$  (Hosmer and Lemeshow 1989, Nagelkerke 1991, Ryan 1997). For all statistical analyses, detection refers to whether a species was captured or not, as opposed to the number of captures;  $\alpha = 0.05$ .

## RESULTS

From 13 April 2007 – 21 April 2009, we sampled 91 transects and 455 quadrats, locating 42 red-backed salamanders. We found individuals in 26 of 91 transects (29% encounter rate). Mean SVL for captured adults was  $40.06\text{mm} \pm 0.90$  SE while mean SVL for captured juveniles was  $27.33\text{mm} \pm 1.40$  SE. Our logistic regression selected a model that explained 30% of the variation in the data ( $r^2 = 0.30$ ) and produced two predictor variables. The first was the standard deviation of organic soil layer pH (SDOrgpH:  $6.50 \pm 2.38$  SE, change in -2 log likelihood = 9.350,  $df = 1$ ,  $P = 0.002$ , Fig. 1). The second was the average mineral soil layer pH (AvgMinpH:  $-1.80 \pm 0.92$  SE, change in -2 log likelihood = 6.376,  $df = 1$ ,  $P = 0.012$ , Fig 2). The model defined the probability of predicting the detectable presence of a red-backed salamander within a

1

transect as equal to  $\frac{1}{1 + e^{-(5.42 + 6.50 \text{ SDOrgpH} - 1.80 \text{ Avg Min pH})}}$ . It correctly predicted

the absence of salamanders in 81% of cases, and correctly predicted their presence in 37% of cases.

Soils throughout the study site tended to be acidic. The average organic layer soil pH across all transects was  $4.62 \pm 0.10$  SE, and the average mineral layer soil pH was

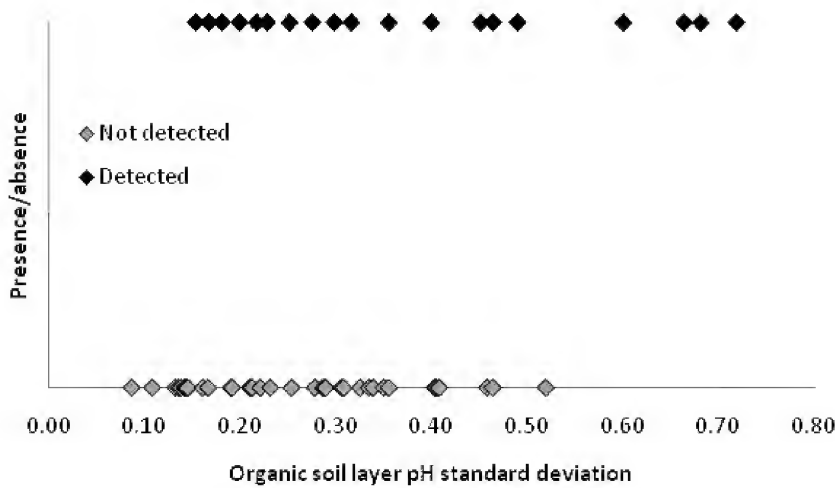


FIGURE 1. Detection of red-backed salamanders as a function of the variability (standard deviation) in pH of the organic layer of soil for transects on C. F. Phelps Wildlife Management Area, Fauquier and Culpeper County, Virginia, April 2007 – April 2009. Detections tend to increase with increased variation in soil acidity.

4.57 ± 0.08 SE. The pH of the organic and mineral layers were highly correlated ( $r = 0.93$ ) and 77% of our sites had organic fractions with  $\text{pH} \leq 5$  and 83% of the sites had mineral fractions with  $\text{pH} \leq 5$ . All of our captures were in soils with a pH between 3.5 and 6.5 for the organic layer and between 3.9 and 5.3 for the mineral layer.

DISCUSSION

The model explained a substantial amount of the variation in presence and absence data. Haan et al. (2007) found similar results in their investigation of *Aneides hardii* Taylor 1941 (Sacramento salamander) where the best of 18 models were able to explain only up to 37% of the variation in salamander detections. Their models tended to focus on soil moisture and soil temperature. However, Faccio (2003) found that *Ambystoma jeffersonianum* Green 1827 (Jefferson salamander) and *Ambystoma maculatum* Shaw 1802 (spotted salamander) presence could be correctly predicted 93.5% of the time based on leaf litter cover, natural cover objects, soil moisture, slope and vertical tunnel abundance. This suggests habitat is a complex multivariate component of terrestrial salamander ecology and that a wide array of habitat features is required to predict their presence. However, our model was more narrow than Faccio (2003) and Haan et al. (2007), focusing entirely on soil pH. This implies that soil pH is particularly important for this area, at least in terms of determining the habitat red-backed salamanders tended to avoid. The low pH in this area may have been a limiting factor that effectively drowned out the signal of all other important habitat features. Our results showing that red-backed salamanders were found only in the sites with lowest mineral soil pH was unexpected. Salamanders are generally thought to prefer neutral soils (Wyman and

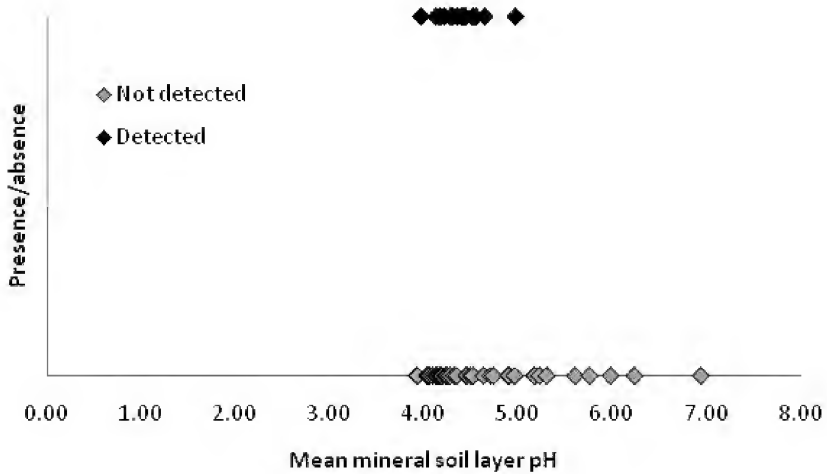


FIGURE 2. Detection of red-backed salamanders as a function of the average pH of the mineral layer of soil for transects on C. F. Phelps Wildlife Management Area, Fauquier and Culpeper County, Virginia, April 2007 – April 2009. Detections tend to decrease as soils become increasingly neutral.

Hawksley-Lescault 1987, Wyman 1990, Sugalski and Claussen 1997). Sugalski and Claussen found that pH was a primary determinant of wild-caught red-backed salamander location in environmental sub-chambers with varying levels of pH, soil moisture and light levels. Wyman and Hawksley-Lescault (1987) found that soils with pH ranging 2.5 – 3 could be lethal for red-backed salamanders and that growth was chronically reduced 45 – 60% in soils of pH 3 – 4. Moore and Wyman (2010) however, described a seemingly healthy population of red-backed salamanders using coverboards overlaying low pH soils (3.1 – 5.2). Our SVL measurements and capture rates are very similar to theirs, implying our population is comparably healthy in generally low pH soils. Moore and Wyman (2010) suggested two hypotheses to explain their findings: 1) other soil constituents counterbalanced the low pH, and 2) the population was locally adapted to low pH soils.

Our model suggests a third: that highly acidic soil is harmful, but individual red-backed salamanders avoid these areas by moving into microhabitats with higher pH's. The variability in organic soil pH across quadrats within in a transect may be picking up on a pattern of soil pH variation that allows individuals to take refuge in high pH sites away from chronically low pH sites, such as movements from chronically low pH mineral soil layers, to more variable (and favorable) organic soil layers, thereby becoming more detectable. This would simultaneously explain the great importance of soil pH in the model, the positive relationship between detections and organic layer soil pH variation and the negative relationship between detections and mean mineral layer soil pH.

The Rappahannock River watershed overlays the Virginia Gold-Pyrite Belt, a geologic formation extending from Fairfax County 225 km southwest to Buckingham County. Gold mining occurred in the watershed region, primarily in the mid-1800's (Sweet 1971). C.F. Phelps WMA contains some abandoned open-pit gold mines, which may explain, in part, the low pH there (Sweet 1980), but because there is little information regarding how extensive the tailings from these mines were, their contribution to the preponderance of low pHs observed at our site is unclear. Nevertheless, our findings imply that a site-specific condition such as pH is an important determinant of the habitat ecology of local amphibian populations. The need to determine the behavioral and adaptive responses of amphibians to soil pH is even more urgent given increasing forest acidification, whether due to mining activity or acidic precipitation (Fenn et al. 2006, Connelly et al. 2007).

#### ACKNOWLEDGEMENTS

We thank Joe Ferdinandsen, manager of C. F. Phelps WMA for his cooperation, along with R. Hughes & Jerry Sims. We thank University of Mary Washington students Carly Byers, Sarah Almahdali, Jennifer Clary, Hillary Adams, and Ramsey Hanna for their assistance in the field. We thank the students of J. D. McGhee's animal ecology classes for Fall 2007 and 2008 for their help in field sampling. We also thank Dr. C. Haas and one anonymous reviewer for their helpful reviews of the manuscript.

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## Botany

### POTENTIALLY HARMFUL CYANOBACTERIA IN VIRGINIA LAKES.

Harold G. Marshall, Dept. Biol. Sci., Old Dominion Univ., Norfolk, VA 23529-0266. During a two year summer survey (2010-2011) of 29 freshwater lakes and reservoirs in Virginia 7 potentially harmful cyanobacteria species were identified, that are known toxin producers. These were *Anabaena circinalis*, *Anabaena spiroides*, *Aphanizomenon flos-aquae*, *Cylindrospermopsis raciborskii*, *Limnothrix redekei*, *Microcystis aeruginosa*, and *Snowella lacustris*. One or more of these species were recorded in 21 (72.4%) of the 29 sites, with 3-4 of these present in 5 (17.2%) of the sites. These 5 locations were Burnt Mills Lake, Lake Smith, Lake Prince, Lee Hall Lake, and Lake Meade. No bloom event, or associated harmful impacts were occurring during these collections, with *A. flos-aquae*, *C. raciborskii*, and *L. redekei* the most common of these taxa. This information is considered preliminary because the collections were limited to a few summer sampling dates per site, with no extensive coverage at these lakes, or were collections taken throughout the year. However, the results are indicative that potentially harmful cyanobacteria are common and may be considered as part of the representative lake flora in Virginia. Undoubtedly, this list of potentially harmful algal species will be expanded with further studies. Supported by the Virginia Department of Health.

## ENVIRONMENTAL SCIENCE

THE BRIGHTER SIDE OF ALGAL BLOOMS: LOCAL AND INTERNATIONAL RESPONSE TO A CENTRAL AMERICAN LAKE IN DISTRESS. A.M. Mojica<sup>1</sup>, M.R. Semcheski<sup>2</sup>, T.A. Egerton<sup>2</sup>, M.T. Muller<sup>2</sup>, & H.G. Marshall<sup>2</sup>, <sup>1</sup>Department of Environmental Sciences and Agriculture, Universidad Rafael Landívar, Guatemala City, Guatemala and <sup>2</sup>Department of Biological Sciences, Old Dominion University, Norfolk, VA 23529. Lake Atitlan in the Western Highlands of Guatemala has been described as one of the most beautiful lakes in the world. This deep (341 m), oligotrophic caldera lake has been characterized as having clean, clear water (secchi ~ 20 m), providing both cultural and economic importance to the surrounding communities. In recent years, the increase of nitrogen and phosphorous input has triggered several harmful algal blooms of the cyanobacteria *Lyngbya robusta*, threatening the economic viability of the lake, and endangering the health of local communities. These algal blooms have also increased awareness of lake water quality. Local and international institutions have undertaken a program of educating citizens in best management practices and training Guatemalan students in limnology concepts and water quality monitoring methods. Additionally, the development of a large-scale, multi-institutional, watershed-wide water quality monitoring program is currently in progress. With increased public awareness and global scientific involvement, a better understanding of bloom dynamics in this lake can be attained, and policy can be put in place to aid the cessation of the current trophic shift and restoration of this lake to pristine status.



**Participating Institutions**

Ferrum University  
George Mason University  
James Madison University  
Liberty University  
Longwood University  
Old Dominion University  
Radford University

Randolph-Macon College  
University of Mary Washington  
Virginia Commonwealth University  
Virginia Military Institute  
Virginia Tech  
Virginia Union University  
Washington and Lee University

**VAS - Winners - Fall 2012 Undergraduate Research Awards**  
Grants of \$500 were award as follows:

**Kyle Sachs**

Department of Computer Science,  
Longwood University  
Faculty Advisor: Robert Marmorstein  
Project title: Low Cost Devices for  
Improving Wireless Reception:  
Analysis of Performance Degradation  
over a Wireless Network.



**Ryan Green**

Department of Biological Sciences,  
University of Mary Washington  
Faculty Advisor: Lynn O. Lewis  
Project title: A study of Chororquine's  
Antiviral Characteristics.



**Christopher Crockett**

Department of Biology, Virginia  
Commonwealth University  
Faculty Advisor: Karen Kester  
Learned Responses to Herbivore-  
Induced Phytochemicals in the  
Parasitic Wasp, *Cotesia congregata*  
(Say) (Hymenoptera: Braconidae)



**Michael Canfarotta**

Department of Biology and Chemistry,  
Liberty University  
Faculty Advisor: Andrew Fabich  
Project title: Characterization of  
Different Mouse Models of *Citobacter*  
*rodentium* Induced Colitis



**Lauren Woodie & Shannon Marwitz**

Department of Biology, Washington  
and Lee University  
Faculty Advisor: Sarah Blythe  
Project title: Pay Attention to What  
You Eat! Developing an Animal Model  
for Diet Induced ADHD



## NOTES

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